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Mine Power Systems Research

(In Four Parts)

1. Trailing Cables

UNITED STATES DEPARTMENT OF THE INTERIOR

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Mine Power Systems Research

(In Four Parts)

1. Trailing Cables

Compiled by Staff–Mining Research

UNITED STATES DEPARTMENT OF THE INTERIOR
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CONTENTS

	Page
Abstract	1
Introduction	1
Trailing cable damage--causes and prevention, James J. Hanslovan	4
Trailing-cable splices--moisture exclusion after flexure, by J. N. Tomlinson	21
Low-voltage shielded cables, by R. H. King and J. Hanslovan	35
Locating trailing cable faults using automated time-domain reflectometry, by Eugene W. Bartel, Angel G. Jordan, and George J. Conroy	51
Medium- and high-voltage trailing-cable splice and coupler considerations, by M. L. Fenger and S. F. Mauser	60
Development of crimp connector and splice-insulating kit for trailing cables, by Walter J. Frank, Jr	76
Recent developments in locating cable faults, by George J. Conroy	91

MINE POWER SYSTEMS RESEARCH

(In Four Parts)

1. Trailing Cables

Compiled by Staff–Mining Research

ABSTRACT

This Bureau of Mines report is devoted to descriptions of investigations pertaining to underground mine trailing cables, their handling, splicing, and the use of couplers.

INTRODUCTION

Damaged trailing cables are an important contributor to coal mine fires and personnel injuries of electrical origin. Bureau of Mines research since 1969 has included an extensive program to reduce the incidence of cable damage and promote the rapid and careful repair of damaged cables. The papers presented herein provide information obtained in both laboratory and inmine investigations.

According to section 18.47 of the Code of Federal Regulations (CFR), Title 30, trailing cables on permissible machines are categorized as unshielded, for use at 600 volts or below, unshielded with 2,000-volt insulation for use up to 1,000 volts on cable reels, cables with either individual conductor shielding or overall shielding of conductors for use up to 1,000 volts, and cables with individual shielding of conductors for use up to 4,160 volts. Cables of the latter construction have also been used at 7,200 volts in specially approved installations. All of these cables must have grounding conductors except for two-wire, direct-current, reel-type applications, where other effective means are provided for frame grounding during a fault. The higher voltage cables must also include pilot conductors, which carry a small monitoring current for determining the integrity of the ground wires.

Current ratings pertaining to the cables are given, either directly or by inference, in Part 18 and Part 75 of the Code of Federal Regulations, and the latter also controls the application of temporary and permanent splices and the requirements for the use and connection of the ground, shield, and pilot conductors. Besides the work described in the papers in this report, Bureau research has included reexamination of cable ratings based on intermittent duty for mining machines and the effects of cable-conductor geometry and connections on intermachine arcing.

Two of the papers discuss the cables themselves, and three discuss cable splices and connections. The remaining two papers discuss cable fault location. In the paper on trailing cable damage, suggestions are made for minimizing problems in reeled cables and drag cables, with recommendations for storage. The shielded-cable article describes progress so far in a study, conducted in cooperating mines, that compares usage factors for unshielded cables, those with individual conductors shielded (SH-D), and those with an overall shield (SH-C). Safety considerations, production impact, and economy are some of the factors discussed. During the period of use covered by this report, SH-C cable met with a fair degree of acceptance by mine personnel, the major complaint being that it is difficult to locate a cable fault or faulty splice because of the shield.

In the report on moisture excluding properties of splices, which describes laboratory experience, attention is primarily focused on the jacket and its adhesive. It has been found that heat-shrink and polyurethane-injected splices require the most care during initial installation if a good moisture seal is to be maintained during flexing. Taped splices were shown to have good moisture protection properties, although their resistance to damage by abrasion is limited.

The paper on crimp connectors for splices describes crimp sleeves developed as the result of a Bureau contract to isolate the specific design factors contributing to a successful connection; it also discusses general requirements for good splice connections. Important conclusions are that the ground wire joint must be allowed to slip while the splice is being made in order to assure equalized tensions among the conductors, and that the internal insulation of the splice can strongly affect the mechanical life of the joints during flexure.

Medium-voltage splices and medium- to high-voltage couplers are the subjects of the next paper. Recommendations are made as to what should be included in a splice kit, what training splicing personnel should have, and characteristics of a good splice. The electrical and mechanical requirements necessary for satisfactory performance of a cable coupler in trailing cable application, where its use could reduce the number of splices made at the face, are also discussed.

The ability to locate faults in trailing cables without removing them from the face area is desired by every mine superintendent, even if the cable will be removed for repair. One reason is that the character of faults can change due to mechanical working of the cable and due to changes in temperature and humidity. A fault that could perhaps be located readily just after it occurred, if the locating equipment were available, might require hours to find after the cable has been removed to the surface. No 100-percent-successful technique has been found, but the promising ones are discussed in the first of the two papers on fault locators. The last paper discusses the technique of time domain reflectometry (TDR), in detail, describing a TDR unit that utilizes a microcomputer to provide a digital indication of fault magnitude and distance.

All of the papers presented are intended to provide information that can be used immediately, rather than to completely describe the research being undertaken. Further information is available in the annual and final reports of the various projects or through the technical project officer. Throughout this report, reference to specific companies or trade names is made for information only and does not imply endorsement by the Bureau of Mines.

TRAILING CABLE DAMAGE--CAUSES AND PREVENTION

by

James J. Hanslovan[1]

ABSTRACT

Stresses that damage coal mine trailing cables were investigated to obtain a quantified description of cable-stress locations, magnitudes, and frequency of occurrence. Stresses occurring in operating mining sections were measured and observed. Answers to questions that arose during the underground investigations were pursued under controlled conditions, both in the field and in the laboratory. Cable-handling suggestions that minimize or eliminate the stresses are summarized in the form of recommendations to mine operators.

INTRODUCTION

Electrical trailing cables that supply power to underground coal mining equipment are frequently damaged. The damages can result in electrical shock and burn hazards to mine workers who must handle the cables. In addition, cable damage often interrupts power to the equipment, delaying production and necessitating cable repairs. The purpose of this research effort was to identify and quantify cable stresses so that cable damage can be reduced, thereby providing a safer and more productive working environment in underground coal mines.

To prevent cable damage, the physical stresses that deteriorate cables must first be identified and quantified. Several authors, including the Anaconda Co. (1)[2] and King (4), have identified the most important cable stresses as being tension, temperature extremes, flexing, twisting, abrasion, cutting and crushing. However, quantified cable-stress values are not available.

In this research effort, methods were devised to measure the magnitudes of several prominent cable stresses. Then, numerous underground visits were made to examine trailing cables in use, and observe and measure the physical stresses in different mining situations. Answers to questions that arose during the underground investigations were pursued further under controlled conditions in the field and laboratory. Cable-handling practices that minimize the stress were identified, and recommendations were made to mine operators that will increase personnel safety, cable life, and productivity. The results of the research were also used to prepare cable-testing standards that are presented in another paper at this meeting.

---

[1]Research was performed while a graduate student at Pennsylvania State University, University Park, Pa; currently, special project engineer, National Mines Corp., Pineville, W. Va.

[2]Underlined numbers in parentheses refer to items in the list of references at the end of this paper.

The research was funded by the U.S. Bureau of Mines under grant G0155197, and George Conroy from the Bureau of Mines Pittsburgh Mine Safety Research Center was the technical project officer. The investigation was directed by Lloyd A. Morley, associate professor of mining engineering, Pennsylvania State University. Robert H. King, instructor of mining engineering (P.S.U.) and James N. Tomlinson, research assistant (P.S.U.) offered valuable guidance and assistance. The author is deeply indebted to numerous mining companies and cable manufacturers for their cooperation in this project.

TEST PROCEDURES

Quantitative values of typical cable stresses can only be obtained in operating mining sections. The measurements must not interfere with the mining cycle or cause delays. These requirements impose strict limitations on the test methods and procedures and prevent detailed measurements of various stress parameters. After much consideration, the following tests were chosen as the most suitable for the underground investigations.

Tension

Tension measurements were performed on both reeled and drag cables. Shuttle-car-cable tensions were measured on operating mining sections, and under controlled conditions at a simulated mine. Reeled-cable tensions on other machinery such as roof bolters, coal drills, and cutting machines were not investigated because they occur relatively infrequently, and workers are likely to give the cable special treatment if they know they are under observation. Shuttle-car-cable tensions are less likely to be controlled by the operator. Because of the congestion in the vicinity of the operating continuous miner, an attempt to measure drag-cable tensions on miners would be inconvenient and dangerous. Consequently, no such measurements were performed on operating mine sections. Instead, an investigation of miner-cable tensions was performed on a nonoperating mining section under controlled conditions.

Tension measurements were made with a Dillon dynamometer (5-inch dial, 1-percent precision) having a tensile range from zero to 2,500 pounds. The instrument was attached to the cable so that all tension in the cable would be exerted on the instrument.

Temperature

Preliminary underground temperature measurements revealed that cable-heating problems occur primarily on machines that utilize cable-storage reels. Consequently, the cable-heating investigation was directed to the measurement of shuttle-car, roof-bolter, cutting-machine, and coal-drill cable temperatures since these machines commonly utilize cable-storage reels.

Two means of measuring cable temperatures were used--heat-sensitive tape and a thermocouple. The heat-sensitive tape (Tempilabels) recorded the highest temperature experienced during the period that the tape was on the cable. Four different ranges of Tempilabels were used to provide a heat-sensitive range from 100° F to 250° F (38° C to 121° C). The thermocouple was an Omega

model 8020 utilizing a surface probe for on-the-spot measurements when the cables were accessible (thus, they may not be the maximum values experienced during an operating period). Temperatures of individual wraps on storage reels were recorded across each layer, and an evaluation was made of cable temperature versus position on the reel. Similar investigations were performed in the laboratory under controlled conditions.

Flexure and Twisting

Cable-bending on storage reels, sheave wheels, pillar corners, and timbers was noted along with the degree of bending and frequency of occurrence. In addition, instances and areas of cable twisting were investigated, and laboratory investigations were performed to simulate the stresses.

Abrasion and Cutting

Since it would be very difficult to quantify cable abrasion, only the parameters that influence the stresses were recorded. These included a list of all objects that abrade and cut cables, and a description of their qualitative intensity and frequency of occurrence.

Cable Diameter

Cable-diameter measurements were performed in an attempt to locate areas of intense cable abrasion and tension. A model 8 Kanon dial micrometer was employed for making measurements along the entire length of cable. Several measurements were performed along a 3-foot section of cable at specific incremental points. The average of the measurements represented the cable diameter for each section. Thus, areas of relatively small diameters (and hence areas of intense abrasion and tension) were identified. In addition, the recorded measurements were compared with diameter specifications published in Title 30 of the Federal Code of Regulations (5).

Jacket Hardness

Jacket-hardness measurements were performed for the purpose of possibly correlating inconsistencies with locations of intense cable stresses. Measurements were performed with a Shore type A2 durometer in the same manner as the diameter measurements. The average of several measurements represented jacket hardness at a specific location.

Crushing

During the underground observations, instances of cable crushing were reported, and cable-handling practices that enhance or minimize the possibility of cable crushing were noted.

Cable Repairs

The location and description of all cable repairs observed during the underground investigations were recorded. The data were used to locate areas of high-stress concentrations.

RESULTS

Underground cable-stress measurements and observations were conducted at seven mines, owned by seven different mining companies located in Pennsylvania, West Virginia, Virginia, and Indiana. One of the mines (mine 7) was visited solely for the purpose of performing controlled miner-cable tension measurements. Visitations in different areas insured a reasonable overall sampling of different mining conditions. Six of the mine sections visited employed continuous-mining equipment and one used conventional equipment. In addition, a longwall section was also visited at one of the mines.

Tensions

A summary of the average and maximum shuttle-car-cable tensions recorded at each mine, according to shuttle-car haul-cycle elements, is tabulated in table 1.

During each shuttle-car load-haul-dump cycle, the cable experienced maximum instantaneous tensions averaging between 310 and 1,170 pounds as illustrated in table 1. In some instances, several of these cable jerks occurred during one cycle increment, with the maximum exceeding 2,000 pounds.

Shuttle cars were permitted to backspool the cable in all seven mines visited. Tensions were highest during backspooling as a result of the sudden change in reel rotation when the shuttle car passed the tie point. The cable reel had its maximum cable load at this point, and the force from the reel momentum was applied to the short section of cable between the reel and tie point. That is, as the car trammed toward the tie point, the cable was being pulled onto the reel; then, as it passed the tie point, the cable was pulled from the reel causing the rotation to instantaneously reverse.

Many parameters besides backspooling can have a significant effect on instantaneous cable tensions. These parameters were identified during the mine visits, and summarized as follows:

1. Reel hydraulic pressure.
2. Type (if any) of cable shock absorber used.
3. Location of the shuttle car in the mine section.
4. Shuttle-car speed.
5. Direction of shuttle-car travel.
6. Mine-bottom roughness and wetness.
7. Tie-point location with respect to shuttle-car tram path.
8. Quantity of cable stored on the reel.

The effects of reel hydraulic pressure have been examined by Giroux (2). Some of the remaining parameters were evaluated by investigating typical tram manuevers of a Joy 21SC shuttle car under controlled conditions at a simulated mine.

TABLE 1. - Cable tension recorded on each shuttle car in the underground mine sections visited, pounds

Mine	Shuttle car	Instantaneous measurement	Shuttle-car location			
			Inby the tie point	Passing the tie point when tramming to the dump	Outby the tie point	Passing the tie point when tramming to the face
1	Off-standard.....	Maximum.....	85	400	200	400
		Average.....	75	350	130	325
	Standard.....	Maximum.....	125	330	100	330
		Average.....	100	310	65	295
2	Standard[1] (case A).....	Maximum.....	490	-	-	-
		Average.....	370	-	-	-
	Standard (case B).....	Maximum.....	750	535	500	600
		Average.....	410	375	335	410
3	Off-standard (case A)..	Maximum.....	975	770	160	535
		Average.....	535	505	125	435
	Off-standard (case B)..	Maximum.....	780	250	100	550
		Average.....	355	225	80	330
	Off-standard (case C)..	Maximum.....	435	2,250	125	1,375
		Average.....	315	1,170	115	1,080
4	Off-standard.....	Maximum.....	325	400	500	520
		Average.....	265	300	205	310
	Standard (case A).....	Maximum.....	400	410	260	780
		Average.....	210	235	145	400
	Standard (case B).....	Maximum.....	275	2,075	190	1,160
		Average.....	175	960	170	505
5	Standard.....	Maximum.....	405	335	300	345
		Average.....	310	305	205	300
	Off-standard.....	Maximum.....	505	390	100	475
		Average.....	310	280	70	315
6	Standard (case A).....	Maximum.....	400	1,875	85	450
		Average.....	325	790	60	365
	Standard (case B).....	Maximum.....	100	1,125	75	640
		Average.....	90	725	60	450
	Off-standard[1].....	Maximum.....	650	-	-	-
		Average.....	450	-	-	-

[1]The shuttle car did not backspool the cable; the tensions listed resulted when the shuttle car trammed away from the tie point.

The effectiveness of two common types of cable shock absorbers was dependent upon the magnitude of the tensions generated by the shuttle car. A spring-loaded shock absorber worked better when unprotected cable tensions were within the range from 100 to 400 pounds, and reduced tensions as much as 50 percent. At instantaneous tensions from approximately 700 to 1,400 pounds, a 14-inch automobile tire was the better shock absorber, reducing tensions as much as 40 percent. Neither shock absorber significantly protected the cable when instantaneous tensions were below 100 pounds, or above 1,400 pounds.

The effectiveness of the shock absorbers was, in turn, dependent upon shuttle-car location with respect to the tie point. If the cable was permitted to contact several pillar corners between the machine and the tie point, instantaneous tensions were not transferred all of the way back to the tie point. Consequently, the section of cable near the machine experienced severe tensions despite the use of a shock absorber near the tie point.

Shuttle-car speed also influenced the instantaneous tensions. Changes in the rate of cable-reel rotation are faster at higher speeds and, consequently, instantaneous cable jerks are more frequent and more intense.

The direction of shuttle-car travel is important because it determines whether cable is spooled up or played out of the reel. Highest tensions usually occur as the shuttle car trams away from the tie point, playing out cable. However, tensions exceeding 1,000 pounds are possible when slack cable develops as the shuttle car makes a turn in the direction of travel while approaching the tie point. The slack cable is quickly reeled-in, jerking the cable when the slack-cable supply is exhausted.

Instantaneous tensions associated with shuttle-car direction of travel and speed are also greatly influenced by mine-bottom roughness and wetness. A rough mine bottom causes shuttle-car bouncing, which, in turn, causes an increased frequency of sudden changes in the speed of cable-reel rotation. Thus, the magnitude and frequency of instantaneous tensions are increased. Mine-bottom wetness is also important in that mud increases the weight of the cable, necessitating higher reel hydraulic pressures.

Tie-point location with respect to the shuttle-car travel entry can also have a significant effect on sudden changes in the rate of cable-reel rotation. A 40-percent reduction in backspooling tensions is possible by locating the tie point 20 feet back in a cross cut, rather than right next to the travel entry.

It might be suspected that a fully loaded cable reel would achieve high reel momentums and, subsequently, high tensions would develop when reel momentum was suddenly changed. The experimental data indicated no significant change in cable tensions when the amount of stored cable was reduced from five to two layers.

Unlike reeled cables, drag-cable tensions depend upon the length (weight) of cable pulled by the machine and the drag resistance (presence of mud) along the mine bottom or rib. After numerous controlled tests in an idle mine section, the average drag resistance between a typical miner cable and a wet mine bottom was found to be 0.8 times the cable weight. An additional 75 to 100 pounds of tension was required to drag the cable around a pillar corner or a timber. Machine tram speed had very little effect on average drag-cable tensions.

When relatively long lengths of cable are pulled, inducing relatively high average tensions (greater than 600 pounds), the instantaneous tensions caused by sudden cable jerks can exceed twice the average tensions (1,200 pounds). Cable jerks usually result from maneuvering the machine while dragging the cable, or tramming over an uneven mine bottom.

Temperature

Temperature measurements of the cable jacket, using both the Tempilabels and the thermocouple, were performed as described earlier. The maximum reeled-cable temperatures measured in six of the seven mines visited are tabulated in table 2. Decreased heat dissipation due to layering frequently resulted in maximum temperatures in excess of 170° F (76° C). In one instance, temperatures in excess of 250° F (120° C) were recorded.

TABLE 2. - Summary of maximum reeled-cable temperatures measured underground

Mine[1]	Machine	Maximum cable temperature, ° F
1	Off-standard shuttle car	<100
	Standard shuttle car	<100
2	Off-standard shuttle car	170-180
3	Off-standard shuttle car	160-170
	Standard shuttle car	230-240
	Roof bolter	130
4	Off-standard shuttle car	240-250
	Standard shuttle car	160-170
	Roof bolter	130
5	Off-standard shuttle car	130
	Standard shuttle car	130
	Roof bolter	130
	Cutting machine	160
	Coal drill	230
6	Off-standard shuttle car	230
	Standard shuttle car	>250
	Roof bolter	110

[1]No temperature measurements were performed in mine 7 because it was visited primarily for the purpose of performing detailed miner-cable tension measurements.

In most instances, a close correlation could be obtained between relative temperatures using both the Tempilabels and the thermocouple. Typical operating jacket temperatures across each cable layer on the reel of a shuttle car traveling a long haul distance are illustrated in figure 1.

Jacket temperatures across each cable layer for a shuttle car traveling a short haul distance and storing a relatively large amount of cable are illustrated in figure 2. In this case, the hottest cable layer (layer 3) was not as close to the reel core as in the previous example (layer 2). In addition, alternate pairs of cable layers at one end of the reel did not have nearly equal temperatures as in the previous case. These phenomena result from the fact that more cable layers remained on the reel during the short haul cycle. As a result, cable temperatures were higher and more consistent, reaching a steady-state value, especially in the inner layers. The phenomenon of increased temperatures with increased layers on the reel was demonstrated at one mine in particular. Cable temperatures decreased substantially (approximately 50° F, 27° C) when the haul distance was increased approximately 100 feet.

An investigation of how the insulation and conductor temperature varied with the jacket temperature was performed under controlled conditions in the laboratory. Five layers of a four AWG, two-conductor, flat, type G cable were stored on a Joy 21SC shuttle-car reel. Conductor, insulation, and jacket temperatures remained nearly equal in the interior cable layers throughout the experiment when the conductors were suddenly subjected to 60 amperes, raising the temperature to 212° F (100° C). Thus, one can infer that the high jacket temperatures measured underground in the interior cable layers on the reel are representative of the insulation and conductor temperatures.

Another temperature stress that is important in both reeled and drag cables is outdoor temperature extremes. In many coal mining areas, winter temperatures are often less than 0° F (-18° C). Since the cables are frequently spooled off the storage reel out-of-doors before they are transported underground, flexure and impact stresses at these low temperatures may be critical. One can actually hear crackling and straining in a cable when it is handled at these low temperatures. Subsequent damage of the insulation and jacket can be dangerous.

Flexure and Twisting

Flexure and twisting of the cables was observed in every mine visited. Although the minimum bending diameter recommended for trailing cables is six times the cable diameter (3), actual bending diameters are often less. These stresses are extremely prevalent with shuttle cars, where the cable is almost constantly bent around sheave wheels, frame edges, mine props, and so on. Some of these stress locations are inconspicuous because of the relatively mild changes in cable direction occurring at the contact points. Although the direction of cable movement may change only a few degrees, actual bending at the point of contact may be sudden. The surface diameter of the object contacting the cable may be very small and, consequently, relatively intense cable-flexure stresses may occur.

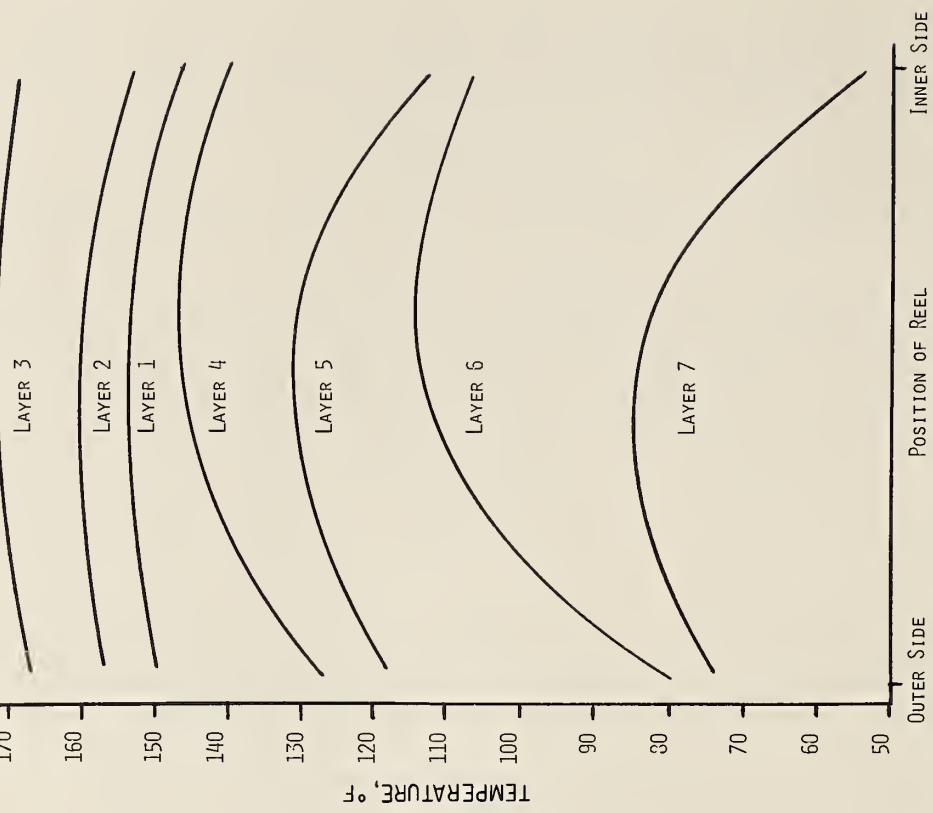

FIGURE 2. - Typical operating cable temperatures on the reel of a shuttle car traveling a short haul distance and storing a large amount of cable.

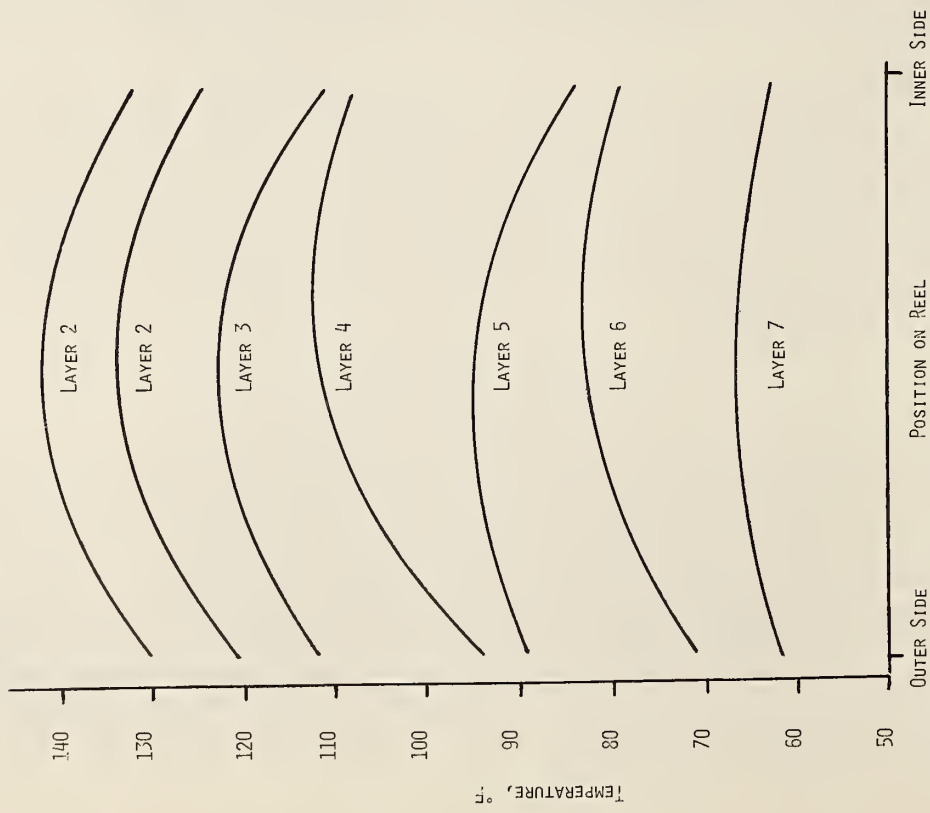

FIGURE 1. - Typical operating cable temperatures on the reel of a shuttle car traveling a long haul distance.

Since the bending and twisting stresses that repetitively occur are most important, stresses occurring during every shuttle-car haul cycle are summarized in table 3. Bending and twisting outby the tie point occur relatively infrequently.

TABLE 3. - Summary of shuttle-car-cable flexure and twisting locations between the machine and the tie point

Location	Angle of bend, degrees	Ratio of bending diameter to cable diameter	Degree of twist, degrees	Length of cable twisted, feet
Cable reel	360	>8:1	0-180	1 -5
Reel core bars or plates	20- 60	3:1 to 12:1	-	-
Cable-layering guide	0- 60	>2:1	-	-
Machine frame edges	0- 60	2:1	-	-
Cable reel to sheave wheel	-	-	0- 90	2 -6
Sheave wheel	0-180	4:1 to 12:1	-	-
Sheave wheel to sheave bracket	-	-	0- 90	.25- .75
Sheave bracket edge	0- 60	>2:1	-	-
Rib corners	0- 90	>4:1	-	-
Tie point	90-360	2:1	0- 90	.25-1

Flexure in drag cables frequently occurs when the cables are transported while in service. Usually, the cables are either looped on the machine or several loops of cable are dragged behind the machine. Continuous-miner cable is often transported on the machine by hanging or wrapping it on machine-mounted cable hangers. At the point where the cable contacts the hanger, the bending diameter may be only four or six times the cable diameter.

Instances of severe twisting in drag cables were also observed. In some cases, the twisting was so severe that it made handling the cable difficult. In many cases, the conductors twisted within the jacket, rather than twisting the entire cable. The jacket itself was not twisted, as evidenced by the untwisted cable identification impressions. Similar twisting within the jacket was duplicated in the laboratory by flexing slightly twisted cable around 10-inch sheave wheels.

Abrasion

Underground observations revealed that cable abrasion takes place in numerous locations, but several occurrences contributed to most of the damage. Abrasion of reeled cables occurred frequently at cable-flexure points inby the tie point. The cable-layering guide, machine frame, and sheave-bracket edges are typical examples of abrasion points.

Unlike reeled cables, drag-cable abrasion occurred primarily along the mine floor and at rib corners. It usually occurred less frequently than with reeled cables, but often damaged long sections of cable in one occurrence. Such items as nails, jagged rocks, and rib corners often caused lengthy cuts, rips, or tears in the cable jacket.

Another source of cable cutting or tearing in both reeled and drag cables occurred at locations where the cable was hung from the roof. Often wire was used to secure the cable. The weight of the cable, in addition to any tension in the cable, often caused the wire to cut into the cable. This problem was especially evident where the cable was bent at the support location.

A summary of common abrading objects, as well as a description of inflicted damage in both reeled and drag cables, is presented in table 4.

TABLE 4. - Summary of objects that commonly damage cables

Object responsible for damage	Cable type damaged	Description of damage
Machine frame edges.....	Reeled.....	Abrasion.
Rib corners.....	Drag and reeled...	Abrasion, cuts, and tears.
Mine floor.....	.....do.....	Do.
Sheave wheels.....	Reeled.....	Abrasion.
Wire for supporting cable.	Drag and reeled...	Cuts and tears.
Mine timbers.....	.....do.....	Abrasion, cuts, and tears.
Wedges.....	.....do.....	Abrasion.
Wire in automobile tires..	Reeled.....	Pierces jacket and insulation.
Clamps.....	Reeled and drag...	Abrasion, cuts, and tears.

Cable Diameter

Significant changes in cable diameter between the load center and the machine were not evident, but in some instances, a slight change was measured. Measurement of miner-cable diameter showed relatively low diameters near the machine. Most miner-cable movement, and hence abrasion and tension occurred nearest the machine also.

Diameter measurements on shuttle-car-cables revealed that relatively low diameters exist inby the tie-point area. This phenomenon was especially obvious in Mine 6. Since the cables utilized in this case were only single conductors and relatively small, a slight change in diameter resulting from abrasion and tension was more obvious than with larger cables. Thus, one might conclude that changes in diameter were not obvious because they were insignificant to the entire cable diameter.

The investigation did reveal an interesting fact. Only half of the cables examined were in compliance with the diameter specifications published in Title 30 of the Code of Federal Regulations (5).

Jacket Hardness

The jacket-hardness investigation revealed some interesting results. Miner-cable jacket hardness increased as much as 10 percent from the machine to the load center. Shuttle-car-cable jacket hardness was found to be as much as 15 percent less inby the tie point than at the load center.

Controlled tests showed that hacket hardness decreased when the cable was abraded or heated, but heat aging caused an increase in jacket hardness. Thus, relatively low jacket hardness inby the tie point was attributed to the higher temperatures and abrasion characteristic of this area. Low miner-cable jacket hardness near the machine was attributed to abrasion.

Crushing

Cable damage frequently results from crushing or pinching. In addition to rock falls and rib falls, movement of equipment in the mine significantly contributes to the damage. The equipment is often mistakenly (and sometimes intentionally) driven over or dragged over the cables.

The most common type of cable crushing probably occurs when a machine runs over or pinches its own cable. Miner cables are often looped on the machine when making a place change, and consequently, are susceptible to runover or damage by the machine itself. Miner and bolter cables are also occasionally crushed against the rib, or against the mine bottom during place changes, as well as when maneuvering in a cut.

Shuttle cars often run over or pinch their own cable in several ways:

1. Run-over as the machine backspools the cable.

2. Run-over as the machine trams toward the tie point.

3. Crushed between the machine bumper and the mine floor as the machine trams toward the tie point.

4. Crushed between the machine frame or bumper and the rib or mine bottom as the machine backspools the cable.

5. Crushed between the sheave wheel and the rib.

Cable Repairs

The location and description of all cable repairs were recorded. In several instances, the cables were out of compliance with State regulations limiting the number of splices.

Another interesting observation was that damage sometimes occurred in clusters along the cable length. This phenomenon may have resulted from the fact that specific cable locations were more susceptible to damage than were other locations. For example, a 30- or 40-foot section of drag cable that was dragged around a sharp pillar corner may have received jacket tears or cuts in several locations.

The intensity of cable damage was best illustrated by examining typical cable life in the mine. Maintenance personnel at six of the mines visited were asked about the average cable life on a continuous miner, roof bolter, and shuttle car at their particular mines. The results tabulated in table 5

illustrate values quoted as average cable life by the head maintenance foreman at each of the mines responding except for mine 3, the values for which represent a calculated company wide average (in excess of 15 mines). The other companies did not keep detailed records of cable life, and the values listed were approximations made by the head maintenance foreman.

TABLE 5. - Average cable life, months

Mine	Continuous miner	Roof bolter	Shuttle car
1.....	18	24	5
2.....	5	2	1
3.....	9.5	5.4	4.5
4.....	3	3	2
5.....	-	9	3
6.....	10	11	3
Combined Average.....	9	9	3

Additional Observations

In addition to the physical stresses already discussed, other sources of cable damage are prevalent in the mine environment. Various types of mine contaminants, such as mine acid water, rock dust, coal, and oil, contribute to the degradation of the cable jacket. Damaged cables are especially susceptible to the contaminants.

Contaminants can also increase electrical deterioration of mine cables by providing low-resistance current paths. Although instances were not discovered in the mines visited, electrical deterioration of one cable resulted in a mine fatality in southern Ohio in 1977. (Specific details were withheld pending further investigations still underway at the time of this writing.) Less severe occurrences have since been discovered in other mines as well.

In addition to damaging cables, cable anchor points are also a personnel hazard. In several of the mines visited, the failure or "pullout" of the tie point was witnessed. A wooden prop and a steel jack were pulled out of position in two of the instances and a chain broke in the third. Not only are the supports violently thrown during the procedure, but personnel can be struck by the cable itself as it whips unrestrained. This hazard cannot be overemphasized.

Finally, instances of exposed conductors in the cables were quite common. Of the seven mines visited, energized conductors were found exposed in cables at four of the mines. Most mine workers agree that such occurrences are typical. In one instance, a mine worker justifiably referred to the cables as "snakes."

In addition to the personnel hazard created by the physically damaged cables, machine downtime also presents a problem. Statistics of machine downtime were obtained at one mine. The data results, presented in table 6,

represents 14 months of operation (February 1976 to April 1977). Cable-related downtime is a significant percentage of total machine downtime, especially in the case of shuttle cars.

TABLE 6. - Cable-related downtime as a percentage of total machine downtime at one of the mines visited

Machine	Cable-related downtime as a percentage of total machine downtime
Loader	29
Cutter	26
Standard shuttle car	80
Off-standard shuttle car	73
Coal drill	38
Roof bolter	61

RECOMMENDATIONS

Cable-handling practices that increase personnel safety, production, and cable life were identified during the investigation, and have been summarized in the form of recommendations to mine operators. Since the physical stresses subjected on reeled and drag cables are often different, handling recommendations for each cable type are discussed separately. Then, recommendations that minimize or eliminate various stresses in all types of trailing cables are presented.

Reeled-Cable Recommendations

1. Cable anchor points should be constructed so as to prevent personnel injury should the tie point be pulled out of position. Using two anchor points will insure that the cable will not whip dangerously should one of the anchor points fail. This precaution will also prevent subsequent cable damage.

2. A rubber-tire shock absorber performed better than the spring-loaded shock absorber at tensions between 600 and 1,400 pounds, but neither shock absorber significantly protected the cable when tensions were greater than 1,400 pounds. The use of a rubber-tire shock absorber is recommended provided it is periodically examined for damage and replaced. However, other types of untested spring-loaded shock absorbers may perform better than the one tested in this investigation.

3. Reel hydraulic pressure should be periodically checked and maintained at a minimum level that prevents the shuttle car from running over its cable.

4. Avoid backspooling shuttle-car cables. If backspooling is necessary, locate the cable anchor point as far away from the travel entry as possible.

5. Minimizing the number of cable-friction points between the tie point and the face will insure the most effective use of a cable shock absorber.

6. When reeling-in slack cable, every precaution should be taken to minimize reel momentum to prevent jerking the cable when the slack cable supply is exhausted. This can be attained by slowly and cautiously reeling-in the cable.

7. Maintaining a smooth mine bottom, especially in the vicinity of the tie point, will help minimize instantaneously high cable tensions resulting from shuttle-car bouncing over an uneven mine bottom.

8. Minimizing shuttle-car speed when rounding pillar corners and passing the tie point will help minimize instantaneously high cable tensions.

9. Cable temperatures can be minimized by minimizing the amount of excess cable stored on the reel.

10. Cable abrasion on the shuttle-car frame can be reduced by assuring that all contact points are smooth and rounded. If possible, install rollers or sheave wheels at contact points to minimize abrasion. This precaution will also reduce flexure damage.

11. Avoid severe cable bending and twisting at the tie point and elsewhere.

12. Twisting between the machine and the anchor point can be minimized by locating the tie point a maximum distance away from the machine travel entry.

13. If possible, locate shuttle-car cable repairs outby the tie point where cable stresses are less severe.

14. Keep sheave wheels and rollers free from mud so that they can turn freely.

Drag-Cable Recommendations

Recommendations for drag-cable-handling practices are as follows:

1. Minimize the lengths of cable pulled.

2. Round pillar-corner edges to minimize cutting or tearing the cable.

3. Prevent the cable from being pulled over jagged rocks, timber, or other sharp objects.

Additional Cable-Handling Recommendations

The following recommendations apply to all types of cables.

1. Store all cables in a warm environment during the cold winter months. If storage facilities are limited, the cold cable should be temporarily stored in a warm environment prior to sending it underground.

2. In instances where cables are tied to the roof, avoid using small-gage, uninsulated wire. The wire has a tendency to cut the cable jacket.

3. Locate all cable routes in entries where they are safe from being run over.

4. Periodically check all cables for damaged areas and electrical deterioration. Make necessary repairs or replace the cable.

5. Minimize cable contact with various oils, greases, and other mine contaminants.

6. Take extra precautions to minimize cable stresses in areas of cable repairs.

REFERENCES

1. Anaconda Wire and Cable Co. How Underground Cables Fail. Ch. in How To Cut Downtime and Extend Cable Life. V. 2, New York, 1975, pp. 6-7.

2. Giroux, D. Protection and Troubleshooting of Coal Mine Electrical Cables. Shuttle Car Reel Test Unit. BuMines Open File Rept. 42(1)-74, October 1972, 102 pp.

3. Insulated Power Cable Engineers Association. Rubber-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy. IPCEA-NEMA Standards Pub., 5th ed. pt. 8, March 1971, p. 9.

4. King, R. H. Underground Coal Mine Trailing Cable Splices. M.S. Thesis, Pa. State Univ., University Park, Pa., June 1974, pp. 29-60.

5. U.S. Code of Federal Regulations. Title 30--Mineral Resources; Chapter I--Mine Safety and Health Administration, Department of Labor; Subchapter D--Electrical Equipment, Lamps, Methane Detectors; Tests for Permissibility; Fees; Subpart D--Machines Assembled With Certified or Explosion-Proof Components, Field Modifications of Approved Machines, and Permits To Use Experimental Equipment. July 1, 1978, pp. 114-121

TRAILING-CABLE SPLICES--MOISTURE EXCLUSION AFTER FLEXURE

by

J. N. Tomlinson[1]

ABSTRACT

Trailing-cable splices are evaluated for moisture exclusion abilities after repeated travel over shuttle-car sheave wheels. Tests are conducted on cables with jackets made of neoprene, cholrosulphonated polyethylene (CSPE), and nitrile butadiene-polyvinyl chloride (NBR-PVC) to 50° C. The results show that some splice kits are effective as received, others are improved with minor but significant changes, and still others must be redesigned to be effective in underground applications. Laboratory results are compared with actual underground splice results. Recommendations for cable preparation prior to splicing are presented.

INTRODUCTION

General

Splicing can create serious weaknesses in portable trailing cables. However, the work reported here points out that some splice kits are effective when properly used and, with minor changes or additions, some of the less effective kits can be considerably improved.

This work was conducted as part of the research under U.S. Bureau of Mines Grant G0155197 with George Conroy as the technical project officer.

Statement of the Problem

Portable trailing cables used in underground mining are generally quite rugged and can withstand a great deal of abuse. However, an extremely local stress such as crushing, pinching, or abrading can result in immediate or eventual need for splice repair. That part of the cable is then highly susceptible to repeat failure since it is difficult to restore the original qualities of the cable.

Splice defects can be traced to (1) the connectors, (2) the insulation and jacketing components, and (3) workmanship. All three are areas of concern for improving splice safety and performance.

The conductors in portable trailing cables are standard for high flexibility but connectors abruptly reduce the stranding to solid conductors and cause failure with repeated bending in a reeling and unreeling operation. Whereas unspliced trailing cable might withstand more than 50,000 bend cycles

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without conductor failure, a well-made splice connection in the same cable can easily fail in only 500 cycles. In terms of usefulness, this may be equivalent to only 10 to 15 production shifts. Quite often, the connections are not of this quality and fail even sooner.

Connector requirements for trailing-cable applications has been studied by the Burndy Corp. under USBM contract H0357100. The result is a new modified crowsfoot connection that is expected to provide improved performance over other trailing-cable connections (1).[2]

Insulation and jacketing give the cable its dielectric and toughness properties, respectively, and, except for the cases of extreme local stresses, these cable parts will last as long or longer than the conductors, assuming there are no temperature abuses. On the other hand, splice insulation and jacketing components might or might not outlast the connections, depending on the splice and the severity of use. The kinds of failure are (1) material failure and (2) joint failure between the splice components and the original cable insulation and jacketing. Often, the failures are a combination of joint failure from bending stresses and material wear from severe abrasions.

The effects of abrasions are usually quite obvious to visual examination since the splice takes on a ragged, worn appearance. However, with joint failure, appearance changes can be rather subtle, and a contaminant such as water and coal dust can enter the splice and create an interconductor fault or serious shock hazard before it is detected.

With short-lived connections, the splices are usually replaced before the insulation and jacketing failures occur. However, with improvements in connector designs, this might not be the case for some splices; the insulation and jacketing might be the weaker link.

Good workmanship is of major importance for effective splice performance. Often, however, the mechanic is rushed and takes short cuts in making a splice. In some cases, the mechanic might not be familiar with a certain splice kit or the instructions. In still other cases, the instructions are not clear or the proper tools and materials are not available to make the splice as the kit manufacturer had intended. Improvements to workmanship will have to come through cooperative efforts on the part of mine operators and splice kit manufacturers.

The work reported here was directed toward evaluating the methods used in rejacketing splices with special attention given to the effects of repeated flexing on the moisture exclusion properties of the splice. Actually, abrasion also should be considered, but it is left for another study. Abrasion effects are generally less subtle and tend to flag pending faults and shock hazards. Additionally, most of the splice flexing and abrasion takes place on the shuttle car itself (5). Although it is unlikely that the amount of flexing can be reduced significantly, it would seem that much of the abrasion can be eliminated or at least reduced with proper care and equipment maintenance.

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[2]Underlined numbers in parentheses refer to items in the list of references at the end of this paper.

Presentation Objective

The purpose of this presentation is to review some of the requirements of splices for underground trailing cables with regard to the rejacketing materials and to point out (1) variations in splice kit designs and performances, (2) the need for care and detail in making a good splice, and (3) the information available in analyzing discarded trailing cable splices. It is hoped that the presentation will benefit both the mine operator and the splice kit manufacturer and help stimulate discussions and informative exchanges.

Presentation Format

General descriptions are presented for the different types of splice kits that were tested, and these are followed by descriptions of the testing machines, the test samples, and the testing procedures. A performance discussion follows this background information. General conclusions and recommendations are then presented as a closing summary.

SPLICE KIT DESIGNS

The various splice kits can be categorized according to their construction by (1) tape, (2) tape and sleeve, (3) expanded boots (including heat-shrinks, prestretched Neoprene and rolled Neoprene), and (4) injected splice coverings. Brief descriptions of each kit are presented to aid the reader in understanding later discussions on performances.

Tape Splices

Two different tape kits were evaluated. In one kit, a soft filler tape is used to reinsulate the connections, and then a glass tape is used to bind the conductors together and reinforce the newly insulated areas. An adhesive cement is then applied over the entire splice areas, and a double application of rubber tape is applied as the final insulation and protective covering.

In another tape splice, the primary insulation is replaced by wrapping each connection with a rubber pad, one side of which has a self-adhering cohesive rubber that holds the pad in place and seals the connection. The conductors are then bound together with a plastic tape and wrapped with rubber tape and a final application of more plastic tape.

Tape With Sleeves

Three different kits using tape with protective oversleeves were tested. Two of the kits use neoprene for the sleeves while the third uses a cross-linked thermoplastic material. One kit uses rubber tape to insulate the connectors, one uses a split neoprene tube and tape, and the third uses a split thermoplastic tube and tape.

After insulating the connections, the splice area is coated with an adhesive cement and wrapped with rubber tape. Next, the tape is coated with a liberal amount of the same adhesive cement and the sleeve is slipped into

place. Two of the kits recommend applying additional adhesive over the ends of the sleeve and more rubber tape. A protective layer of vinyl plastic tape is then applied over the rubber tape.

Expanded Boots

The expanded boots are the heat-shrinks, the prestretched neoprene, and the rolled neoprene designs. They are similar in that they use a factory expanded boot as the final protective splice covering.

The heat-shrink boots are made of crosslinked polyolefin tubes, which are heated, expanded radially, and allowed to cool. Once cooled, they are unable to shrink back to their normal size and so remain enlarged until they are again heated to some minimum temperature for example, 135° C or 275° F). Heat is usually applied with a propane torch or exothermic heat pack.

The inside surface of the heat-shrink boot is coated with an adhesive (usually the hot-melt type) that softens with the applied heat and bonds and seals the boot to the cable jacket. Some designs also include additional short lengths of heat-shrink tubing to be applied over the ends of the boot for additional abrasion resistance and contaminant exclusion. Most of the boots are extruded and cut to length and then ground to a slight taper at the ends. One design is molded with taper at the ends. Thermochromic paints are sometimes used as a means of indicating sufficient heating for proper shrink and adhesive flow. Smaller heat-shrink tubes are used to reinsulate the individual power conductors.

The prestretched boot design uses a radially expanded neoprene tube on a removable plastic core. The core is removed by progressively collapsing it in a spiral fashion, from one end to the other, allowing the tube to recover onto the cable. A rubber adhesive is applied under the ends of the tube after it is recovered in place. Split-tube rubber insulators and tape are used over the connectors, and the conductors are bound together with plastic tape.

The rolled boot has the appearance of two rubber toroids side by side on the same axial support tube. It is made by radially expanding a tubular neoprene sleeve and then rolling both ends toward the middle to form the toroids. Once in place over the splice, the support pieces are removed and the sleeve is unrolled, allowing it to recover onto the cable. A mastic material is used as the adhesive sealant under the rubber sleeve. The ends of the sleeve are taped for additional sealing and scuff protection. Insulation components for the rolled boot splice are either split tube and tape or smaller rolled boots, depending on the kit.

Injected Splices

In the injected splice, the bare conductors are first insulated with vinyl electrical tape. Next, the general splice volume is enclosed with a PVC blanket. A polyurethane sealant compound is then mixed in a special cartridge and injected into the splice through a valve in the PVC blanket. The sealant solidifies in a few minutes and the splice is completed.

SPLICE EVALUATION METHODS

Eleven different splice kits were evaluated on No. 4 AWG, flat neoprene, two-conductor, type G cables and round chlorosulphonated polyethylene (CSPE) and nitrile butadiene rubber-polyvinyl chloride (NBR-PVC) three-conductor, type G-GC cables. The kits consisted of two tape, two tape-and-sleeve, five heat-shrink, one prestretched sleeve, and one injected splice. Additionally, the cross-linked thermoplastic tape-and-sleeve kit and the rolled-boot splice kit were evaluated on flat No. 2 AWG, neoprene, two-conductor, type G cable. Some of the heat-shrink kits were tested with different adhesives as the manufacturers made changes in compounding to improve performance.

The splice kits were evaluated on their ability to retain good moisture exclusion under repeated travel over shuttle-car sheave wheels. Tests were conducted using the closed-loop figure-8 splice-testing machine (fig. 1) and the figure-S splice-testing machine (fig. 2).

With the closed-loop machine, the test samples are prepared on 7-foot lengths of cable, and the ends of the cable are joined with nylon webbing to figure eights (4). The test cables are then mounted on the sheave wheels and driven like a belt. The two sheave wheels are slightly cocked with respect to one another so that the test cable does not rub at the crossover point. As a splice travels over the wheels, it bends first in one direction and then the other. The cycle rate for most of the flexing was 20 or 30 cycles per minute. (A cycle is defined as one complete trace through the figure-8 pattern.) Cable tensions of 100 or 150 pounds were set with the air cylinder and pressure regulator.

The figure-S machine causes the splice to trace out an "S" as the carriage travels back and forth. Like the figure-8, this machine causes the splice sample to bend first in one direction and then the other. The machine was used at the cycle rate of 2-1/2 times per minute to compare the result of low-cycle-rate testing with testing done at 30 cycles per minute on the figure-8 machine. The figure-S testing machine was developed on two earlier Bureau of Mines grants G0101729 (6) and G0133077 (2, 7).

With repeated flexing on the figure-8 machine, the temperature of laboratory samples tended to level off near 40° C after about 1,000 cycles. In order to conduct tests at higher temperatures, the samples were heated with a hot-air gun as they cycled over the sheave wheels. Typically, they were warmed to 50° C in about 3,000 cycles and maintained at this temperature for any additional test cycles. The temperature of 50° C was considered to be representative of those on reeled shuttle car cables, based on actual field measurements. Additionally, laboratory experiments have shown that cables of of the type used here tend to demonstrate jacket surface temperatures on the order of 50° C when the conductor temperatures are at their rated 75°C temperature and the cables are in 25° C free air (5).

Splice test samples were prepared without using connectors and without particular concern for the primary insulation parts. The connectors were

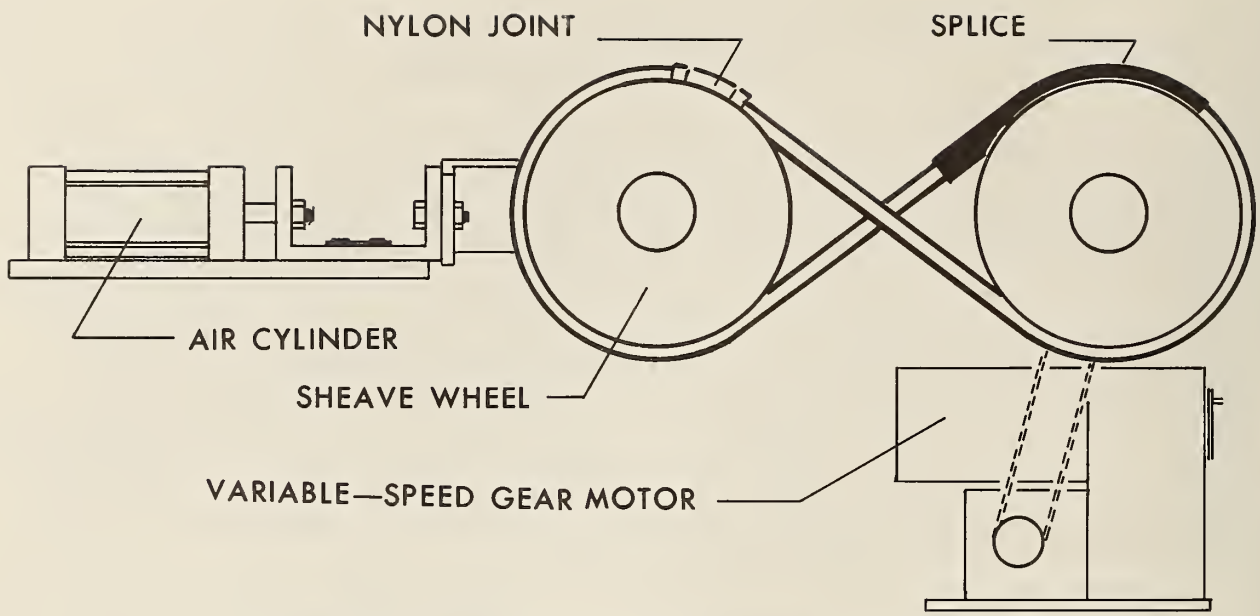

FIGURE 1. - Closed-loop figure-8 splice-testing machine.

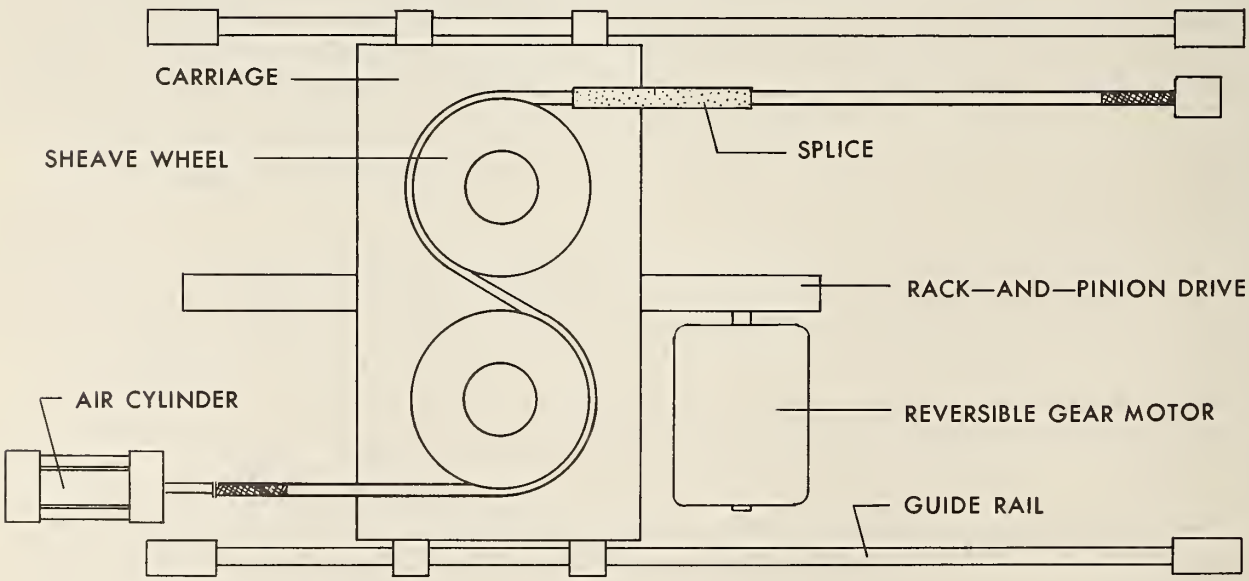

FIGURE 2. - Figure-S splice-testing machine.

eliminated in order that the jacketing materials could be evaluated for any number of flex cycles without being limited by connector failure.

In the initial testing, the splices were prepared on the two-conductor flat cable by removing insulation from both the black and the white conductors as shown in figure 3. The voids were then filled with cotton wicking (fig. 4) and covered with the splice rejacketing materials. The wicking absorbed any water that entered the splice ends and reduced the electrical resistance

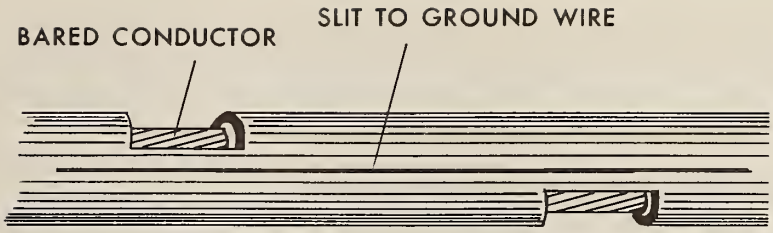

FIGURE 3. - Cable insulation and jacketing removed in preparing simulated test splice.

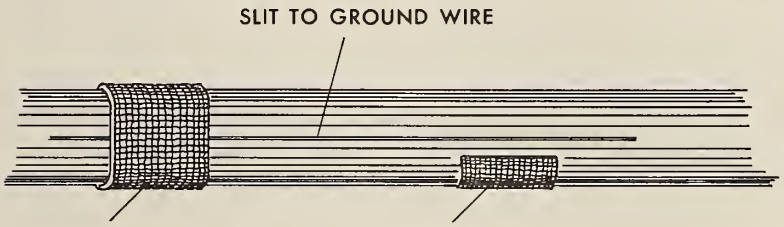

FIGURE 4. - Use of wicking for filling voids and bridging power conductors with the ground wire for moisture detection.

between the power conductor and the uninsulated ground wire. The resistance changes were detected with a megger.

Samples with the wicking were flexed 500 to 1,000 times, water soaked for 16 hours, tested with the megger, and recycled on the flex machine if moisture had not penetrated the splice to where it could be detected. Once failure had been determined or the sample had sustained a sufficient number of flex cycles, it was dissected lengthwise and inspected for failures.

As the testing advanced, it was determined that visual examination of the dissected splices was a sufficient evaluation method, and so the wick and the water soaking were eliminated. Also, splice samples were reduced to 6-inch lengths in some cases without affecting the test results, and as many as five samples were cycled simultaneously in a single figure-8 test loop. The samples in the test "chains" were then compared for performance under identical conditions. This was especially helpful in comparing samples that were tested to 50° C. It also conserved materials and speeded up the testing.

SPLICE KIT PERFORMANCE

The figure-8 splice-testing machine provided totally unexpected data for some splice designs. The results are presented in a discussion format along with recommended changes, which were easily implemented and significantly improved splice preformances. The results presented here are extracted from Annual and Task Completion reports prepared in the course of this investigation (4-5).

Tape Splices

The two tape splices are among the more flexible types and the design that uses the vinyl tape as the final protection layers was essentially unaffected by repeated cycling over the shuttle-car sheave wheels. The splice with the exposed rubber tape, however, deteriorated from stresses other than simple flexure.

In the case of the soft rubber tape, the contact pressure with the sheave wheel causes the tape to extrude and thin-out with repeated cycling. Also, if the splice samples are not perfectly alined with the sheave-wheel grooves, as is the case with the figure-8 machine, then there is a tendency for the soft rubber tape to be extruded even more as the splice tries to ride up on the rim of the wheel. The extruding is completely eliminated, however, when an overlayer of vinyl tape is used as the final splice covering, and the effects of repeated travel over the sheave wheels are practically nil. The soft splices can be destroyed on the figure-8 machine in only 100 cycles without the tape. With the vinyl overlayer, the splices easily withstand more than 10,000 cycles.

Testing to 50° C emphasized any irregular lapping of the tape layers, but the cover integrity was not affected at this temperature.

Soft-rubber-tape splices were the only underground tape splices compared with the laboratory samples. The soft rubber on these splices had been abraded as well as extruded. The appearances were quite similar to those of the lab samples tested without the protective vinyl tape.

Tape-and-Sleeve Splices

The two splices described as using Neoprene oversleeves were the first splices of this type to be evaluated during this test program. The splice described as using a cross-linked thermoplastic sleeve was developed after the initial testing and incorporated most of the recommendations for improvements generated in the earlier testing.

The tape-and-sleeve splices are considerably better performers if the sleeve ends are taped. Additionally, it is important that any soft rubber tape be covered with a protective overlayer.

Splices tested without the tape-down sleeve ends were subject to considerable end lipping; that is, the sleeve ends separated from the underlayers of tape or the tape and the sleeve separated from the cable jacket. The use of soft rubber tape alone, however, is not recommended for holding down the sleeve ends, since it tends to be extruded with repeated cycling over the sheave wheels and also causes serious twisting when the splice is not perfectly alined with the sheave-wheel grooves. In simulated test samples, the unspliced cable conductor failed in less than 500 cycles as a result of the twisting. As with the rubber tape splice, vinyl plastic tape will protect any soft rubber end tapes and reduce the friction to allow the splice to center itself in the sheave groove.

Another important consideration is the tightness of fit for the splice sleeve. Test results show that the sleeve needs to fit snuggly over the entire length of the splice, otherwise the sheave wheel can cause a twisting action as the splice settles into the groove. One solution is to build up sufficient tape layers to accommodate the sleeve dimensions, but this can result in extremely bulky splices in some cases, thus exchanging one problem for another. Splices made with "undersized" sleeves, for example, a type W sleeve on a type G cable, yielded the best test results. Less tape was required and the splices had smaller profiles.

With the suggested modifications, the tape-and-sleeve splices easily withstand repeated flexure at temperatures of 50° C.

Splices recovered from actual mine use confirmed most of the laboratory results and added to the data. Often the sleeves did not fit tightly over the splice, and the rubber end tape, if used, was worn. The results were severe end-lipping that was sometimes advanced all the way into the connectors. In many cases, the adhesive bonds had failed between the underlayers of tape and the cable jacket and between the tape and the sleeve itself. Many samples also indicated that the rubber tape was not properly stretched when applied to the splice.

There is also the problem of centering the sleeve over the splice. A classic example was one in which the sleeve was moved onto the splice until it covered only half of the first connector. At this point, the mechanic must have encountered some difficulty in placing the sleeve and simply covered the remainder of the splice with friction tape. Obviously, better instructions and training would be beneficial here.

Expanded-Boot Splices

Heat Shrink Boots

There are almost as many performance levels for the heat-shrink splice kits as there are manufacturers. Of the eight sleeve and adhesive combinations evaluated, only two might be considered top performers, and their effectiveness is directly related to their adhesives.

Typically, the better performing heat-shrink boots demostrated very little end-lipping on the Neoprene, CSPE, and NBR-PVC cable jackets at temperatures of 25° to 50° C. The fatigue in the adhesive joints for the better splices was almost always characterized by slight adhesion failure with the cable jacket and/or slight cohesion failure. The poorer splices, on the other hand, generally showed significant cohesion failure or significant adhesion failure with the cable jacket and/or the boot.

Test temperatures had considerable effect on the test results for two of the poorer heat-shrink kits. The adhesive for one of the kits softened near 45° C and the boot could easily slide along the test cable at this temperature. At lower test temperatures, the same adhesive showed adhesion failures with the three cable jacket materials and the boot itself.

Another kit demonstrated good resistance to end-lipping for test temperatures below 40° C, but at temperatures approaching 50° C, the samples failed in adhesion with either the cable jacket or the boot. In this case, the adhesive did not wet the cable jacket and boot sufficiently, because its softening point was too high.

Another heat-shrink kit experienced aging problems. Samples which were tested 6 weeks after preparations experienced complete adhesion failure at the boot and adhesive joint line. This is a very serious type of failure since

time alone was the influencing factor. Also, since trailing cables are expected to operate warm, such aging might even be accelerated in actual use.

A heat-shrink splice with a mastic sealant was also evaluated. The mastic, however, was too low in cohesion to provide sufficient bond strength and moisture sealing. Flexing caused the cable and boot to separate allowing water to enter the splice in almost every test sample of this type.

Heat-shrink splices are highly dependent on their adhesives for good moisture exclusion. The sleeves are relatively stiff with a tendency to pull away from the cable jacket at the ends. The adhesive needs to bond well to both the cable jacket and the boot and, at the same time, have good cohesive strength.

On flat cable, the squeeze-out pressure is less on the flat parts of the cable than on the round parts, therefore marginal adhesion generally shows up on the flats. Also, the effects of insufficient adhesive material is brought out on the flat parts of the cable. As the heat-shrink boot recovers, the adhesive is pressed thin on the round parts of the cable and builds up over the flat areas. This buildup is helpful in providing a filling action which, in turn, increases the squeeze-out pressure on the flats. If the boot lacks adhesive material, voids are usually found along the flat parts of the adhesive joint. Insufficient adhesive was found only in some experimental samples tested in the course of this evaluation.

The actual mine splices that were examined had good adhesive bonds near the splice ends. The mine samples were one of the type found to give the best results in the laboratory tests. The splices also provided good examples of voids within the central part of the splice. These voids were caused by bulky connections such as large square knots in the ground wires. They emphasized the need for good moisture exclusion at the ends of a splice since the voids would otherwise provide collection points for contaminants.

A small number of laboratory heat-shrink samples were tested on used cable to temperatures of only 40° C. The results of that limited testing emphasized the poor squeeze-out and poor wetting characteristics of one adhesive. Similar results were obtained when the same kit was tested to 50° C on new cable.

Prestretched Sleeve

The prestretched sleeve samples showed no tendency for end-lipping even after 10,000 flex cycles. Its high flexibility and constant tendency to recover onto the cable makes this Neoprene covering effective against repeated flexing.

A very small mine sampling of prestretched-sleeve splices was examined. The results were similar to those observed with the laboratory samples.

Rolled-Sleeve Splices

The rolled-sleeve splice kit is relatively new and, at this writing, has only been tested on flat neoprene cable. The design shows good flexibility and moisture exclusion properties. No mine samples were examined.

Injected Splice

The injected splice performed best on flat Neoprene cable below 40° C. At temperatures near 50° C and on the CSPE and NBR-PVC cables, the amount of lipping increased from practically none to 1-1/2 inches or more in 5,000 cycles.

Shelf life is a very important consideration with this design. Kits held in storage for 9 months demonstrated very poor adhesion to the cable jackets and lipped over most of the splice length after 5,000 flex cycles on the figure-S test machine.

No mine splices of this type were examined.

Cable Preparations

Most of the test data were gathered on new cables, but evaluations were also made on used cable. In both cases, the required degree of cleanliness depends upon the splice kit design. The heat-shrink and polyurethane-injected splices require the most care since they rely on good adhesion to the cable jacket for an effective moisture seal. Splices using stretched tapes and stretched sleeves require less care in cleaning because they are less dependent on adhesive strength, as the result of the constant tendency of the tapes and sleeves to recover onto the splice.

Trichloroethane, the solvent packaged with a small wiping cloth in many of the kits, was found to be effective in removing mold-release agents on new and used cables and most other contaminants found on underground trailing cables. In the case of rough cable jackets, however, solvent wiping alone is not always sufficient; the additional step of abrading the cable with a medium to coarse emery cloth is recommended. The abrading exposes "uncontaminated" jacket material for improved adhesive bonding. This is especially important along the embossed identification strip of the cable where contaminants tend to collect, and most important for flat cable since the embossing is usually located on the flat area where good bonding is already more difficult. It is recommended that the embossing be abraded away where practical; otherwise, a direct channel can be created for contaminant penetration.

TESTING EFFECTIVENESS

The simulated laboratory testing has provided valuable data for determining effective moisture exclusion for various splice designs. In addition, comparisons with underground splices have supported many of the results interpretations. The splice-testing machines have provided a means of evaluating the effects of flexure and have helped to uncover other and more subtle stresses imposed on splices from the simple action of traveling over shuttle car sheave wheels.

The splice evaluations were based on at least 5,000 flex cycles in most cases. This could be equivalent to about 2 months of use underground. Today's splices do not last this long. However, with order-of-magnitude improvements in connector designs, splices will not be replaced as frequently, and a 2-month life and longer is realistic.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The following conclusions are based on splice evaluations using the figure-8 and figure-S splice testing machines. One must keep in mind that simulated splices were used and that the emphasis was placed on cable jacket replacement parts and their effectiveness in excluding moisture with repeated flexure to temperatures of 50° C.

1. Each of the splice kits is about as effective on CSPE and NBR-PVC as it is on Neoprene.

2. Splice designs need to avoid exposed soft rubber tape. An overlayer of vinyl tape prevents extrusions and reduces frictional drag which otherwise can cause conductor failure from twisting.

3. Heat-shrink designs are particularly sensitive to good adhesive flow and surface wetting. Poor adhesive squeeze-out is a potential joint failure, especially on flat and soiled cable.

4. Low-softening-point adhesives can improve flow and surface wetting during splice boot installation; however, too low a softening point can result in adhesive failures at operational temperatures.

5. Slight temperature changes can make the difference between an effective and ineffective adhesive joint. When the test temperature was raised from 40° C to 50° C, one kit experienced adhesion failure and another experienced the adhesive softening to the point of total cohesion failure.

6. Some adhesive joints can age rapidly causing total joint failure. This is extremely important for reeled trailing cables since they are often exposed to warm temperatures, which can accelerate the aging.

7. Good cable preparations is necessary for effective splices. This is especially true for the adhesive-sensitive designs such as the heat-shrink and injected splices. Solvent cleaning with trichloroethane and abrading with emery cloth are effective preparation methods.

8. Reactive systems such as the polyurethane splice have a limited shelf life. Users need to be aware of the time limitations and the kits should be well marked with expiration dates.

9. Splice coverings such as the tapes, tape-and-sleeve, prestretched Neoprene boot, and rolled-boot are flexible and have a continuing tendency to recover onto the splice. This "forgiving" characteristic makes these coverings ideal for the repeated bending that occurs with reeled shuttle-car cable.

10. Splice instruction sheets should clearly illustrate step-by-step procedures in making a splice. They should be field tested and updated as necessary.

11. Spent trailing-cable splices contain a wealth of information for helping to improve splice kit design and workmanship. Rather than being discarded, they should be dissected and evaluated by coal operators and kit manufacturers for maximum benefit and safety for the industry.

REFERENCES

1. Frank, W. J., Jr. Development of a Crimp Connection for Trailing Cable Splices. BuMines Open File Rept. 58-77, December 1977, 89 pp.

2. Hanslovan, J. J. Trailing Cable Stresses in Underground Coal Mines. M.S. Thesis, Pa. State Univ., University Park, Pa., May 1978, pp. 58-59.

3. King, R. H. Underground Coal Mine Trailing Cable Splices. M.S. Thesis, Pa. State Univ., University Park, Pa, June 1974, pp. 21-26.

4. Morley, L. A., J. N. Tomlinson, R. H. King, and D. E. Kline. Electrical Materials Analysis--Mine Cable Splices. BuMines Open File Rept. 90-78, August 1976, 107 pp.

5. Morley, L. A., J. N. Tomlinson, and R. H. King. Electrical Materials Analysis--Mine Cable Splices. Task Completion Report on USBM Grant G0155197, Oct. 30, 1977.; available for consultation at Pa. State Univ., University Park, Pa. (J. N. Tomlinson).

6. Pennsylvania State University. Evaluation of Mine Electrical Systems With Respect to Safety, Technology, Economics, and Legal Considerations. BuMines Open File Rept. 70-73, 1973, 440 pp.; available for reference at Bureau of Mines facilities in Pittsburgh, Pa., Twin Cities, Minn., Denver, Colo., and Spokane, Wash., and at the Central Library, U.S. Department of the Interior, Washington, D.C.; and from the National Technical Information Service, Springfield, Va., PB 225 475/AS.

7. _____. Mine Electrical Systems Evaluation. BuMines Open File Rept. 76-75, 1974, 501 pp.; available for reference at Bureau of Mines facilities in Pittsburgh, Pa., Denver, Colo., Spokane, Wash., and Twin Cities, Minn.; at the U.S. Department of Energy's facility in Morgantown, W. Va.; at the Central Library, U.S. Department of the Interior, Washington, D.C.; and from the National Technical Information Service, Springfield, Va., PB 245 926/AS.

LOW-VOLTAGE SHIELDED CABLES

by

R. H. King[1] and J. Hanslovan[2]

ABSTRACT

An investigation of the feasibility of shielding low-voltage trailing cables in underground coal mines is described. Both laboratory and underground installation results are presented. The main objective of shielding is to reduce the electrical shock hazard; however, several problems will be encountered by mine operators who install shielded cables. Parameters related to such items as purchasing, splicing, troubleshooting, safety, and reliability are discussed. Some of these problems can be minimized by changes in cable constructions and shuttle-car reeling-device components. Both SH-C and SH-D constructions are considered.

INTRODUCTION

Since the time that underground mining equipment became electrified, a number of fatal and nonfatal injuries occurred that were associated with the use of low-voltage trailing cables. In order to reduce the potential electrical-shock hazard from these cables and thus improve safety, shielding was proposed. However, it was not a certainty that the shielded construction was capable of withstanding the harsh underground coal mine environment. The objective of the research described herein was to evaluate the feasibility of utilizing shielded low-voltage trailing cables in underground coal mines. Both SH-D (individual phase-conductor shields) and SH-C (a single shield over the entire phase- and grounding-conductor assembly) cables with braided copper wire and combination nylon-and-copper shields were studied.

The efficient use and operator acceptance of shielded cables is dependent on several parameters. First, the parameters that affect the safety, cost, reliability, and life of shielded cables are listed and discussed. Next, the items that could be evaluated in the laboratory are analyzed. Then the underground coal mine measurements and observations used to evaluate the other parameters are described. Finally, conclusions and recommendations are presented.

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contributed significantly in his capacity as technical project officer. The Mine Electrical Systems Research group of the Pennsylvania State University attacked this problem with a team effort and the authors would liketo acknowledge the contributions of L. A. Morley, the project director, and James N. Tomlinson. Peter A. Sopko conducted much of the initial investigation before he graduated and accepted a position with the Bethlehem Mines Corp. (12).[3] Mining companies and cable manufacturers also cooperated in this project. United States Steel Corp., Peabody Coal Corp., Cyrus Wire and Cable Co., and the Okonite Co. were the major contributors.

PARAMETERS INVESTIGATED

The parameters that affect the performance of shielded trailing cables that were defined by and investigated in the research are listed as follows:

1. Electrical-shock-hazard protection.
2. Currents induced in grounding conductors.
3. Grounding-system integrity.
4. Maintenance testing (preventive and fault location).
5. Purchasing and operating costs.
6. Availability.
7. Flexibility.
8. Splicing and coupler installation.
9. Outside diameter.
10. Stiffness.
11. Nuisance tripping of circuit breakers.
12. Weight.
13. Cable construction.

To determine whether or not shielded cables were safer than nonshielded cables, Mine Safety and Health Administration (MSHA), U.S. Department of Labor, reports of fatal and nonfatal accidents were examined (5, 10). It was found that of 180 cable-related accidents, 159 could have been prevented by shielding; and of 8 fatalities, shields could have prevented 5. In compilation, only those accidents pertaining to shock were included (neglecting injuries such as tripping over cables, straining the back while moving, etc.) In

[3]Underlined numbers in parentheses refer to items in the list of references at the end of this paper.

addition, it was assumed that cables carrying direct current could be shielded even though it is not present cable-manufacturing practice to shield direct-current cables.

The major injury causes were as follows:

1. Failing to properly disconnect and tag a cable prior to making a splice.

2. Handling cables with bad splices.

3. Handling cables with areas of defective insulation.

A properly maintained shielded cable would have definitely prevented injury in the first and last cases (provided the circuit breaker was functioning properly). If splices in shielded cables were made properly with the shield reinstalled, shielding would have also prevented injury in the second case. However, if the shield would not have been replaced within a splice, the cable would not be any safer at the spliced region than a nonshielded cable.

The problems of induced voltages and circulating currents in unsymmetrical cables would not be eliminated in shielded cables. Contrary to common belief, these problems could only be eliminated by using symmetrical cables operating under a balanced three-phase load (6, 13).

Since the shield would be in electrical contact with the grounding conductor along the entire cable length, it might be expected that grounding-conductor breakage would not significantly affect continuity. Conversely, in nonshielded cables, grounding-conductor breakage could be a very serious safety hazard. This hypothesis was tested in the laboratory, and the results are presented in a later section of this paper.

It is much easier to conduct preventive-maintenance (nondestructive direct-current dielectric-withstand testing) on installed shielded cables than nonshielded cables. Leakage currents can be detected at any point since in the SH-D construction, the entire conductor insulation is surrounded by a grounding medium. Even the SH-C cable allows leakage-current detection between the phase-conductor insulation and jacket. Such testing is impossible with a nonshielded cable.

One of the most important factors associated with shielded cables will be the higher purchase costs. Most manufacturers agree that shielded cables will ultimately cost 10 to 20 percent more than their nonshielded counterparts. However, cables purchased on an experimental basis for underground test sites cost 22 to 149 percent more than identical nonshielded cables. Furthermore, extra components in a shielded-cable splice were expected to increase the SH-D kit price by $1.50, or about 20 percent of total cost.

Some cable manufacturers revealed that large capital investments would be necessary to manufacture shielded cables in large quantities. Consequently,

some recommended a 1- or 2-year tool-up and inventory-disposal time to be included in any shielded-cable regulation.

Sources in the literature cited the flexibility of shielded cable as an important consideration (3). Since the Canadian Electrical Code requires the use of shielded cables (1) for coal-mine applications greater than 125 volts, comments about Canadian experiences were obtained. One Canadian stated it was his experience that shielded cables were much less flexible than nonshielded (7). Furthermore, he related that shielded cable was more susceptible to damage from flexing. Another Canadian, an Inspector of Mines, Electrical, was able to provide historical information for an alternating-current shuttle car using shielded cable in a developing coal mine. The operators claimed that the SH-D cable did not withstand the harsh mine environment. However, the inspector states

> I am convinced, however, that their report was not unbiased, since they particularly favor a cable design using conductive rubber shielding (2).

As a clarification, rubber shields are also known as semiconducting shields.

Shielded-cable splice time was predicted to be longer since there are two additional steps:

1. Removing the shield and bedding tape from around the primary insulation.

2. Replacing the shield after the conductor was joined together and reinsulated.

The splice conductors can be reshielded by placing a single shield sheet, a tube of braid, or double-layered tape over the joint area. Shield continuity can be obtained by soldering or simply taping the repair shield to the original shield. The results of laboratory tests and underground repairs of shielded cables will be covered in the next two sections of this report. Additional time is also required for coupler installation because an extra connection is needed for the shields.

Since shields increase the diameter of the cable, larger entrance glands and splice jackets may be necessary. The slightly larger diameter also causes a reeling-application problem. Simply, as the cable diameter increases, the length that can be placed on the reel decreases, thus more frequent load-center moves or more shuttle-car back-spooling is required. It is necessary to modify the spooling-and-reeling mechanism to overcome this problem.

The advantage of having a grounding medium (shield) completely encircle the power conductors can cause fault-location problems. If the shielded cable is damaged enough to allow leakage currents to trip the breaker without noticeably affecting the outer jacket, the damaged area is difficult to locate.

Shielded cables can weigh as much as 30 percent more than nonshielded cables of the same size and design. The weight factor is a problem in transporting, handling, and reeling shielded cables. In addition, the shield makes the heavier cable stiffer and less flexible, which compounds these problems.

Finally, most of the previous parameters are affected by the cable design. That is, there is more than one way to make a shielded cable, and the most efficient construction is the one that minimizes the problems from the previously discussed sources.

LABORATORY INVESTIGATIONS

Tests were performed at the Penn State Mine Electrical Research Laboratory to investigate some of the parameters presented in the previous section. One of the tests involved measurements to determine the amount of shield coverage necessary for complete shock protection. A sharp object (a six-penny coated nail with an average diameter of 0.0857 inch) was driven repeatedly into the cable. A six-penny nail was chosen because it represents one of the smallest objects used in a coal mine that might be driven into a cable. The contact resistance between the penetrating nail and the shield was monitored with a portable Kelvin bridge or an ohmmeter. Copper braid, nylon-copper braid, tape, and wire shield types were tested.

In order to insure that the shield is effective in preventing electrical shock, a low-resistance path to ground must be present if a mine worker contacts an exposed phase conductor or forces a conducting object through the insulation into the conductor; that is, the phase current should pass into the grounding circuit rather than into the worker's body. Therefore, the grounding-path resistance must be considerably lower than 1,000 ohms--one of the lowest resistance values estimated for the human body (4, 11).

The tests revealed that with one exception, SH-D cables with a nylon-copper braid, copper braid, or a metallic tape shield all yielded resistance values lower than 0.1 ohm. The exception was a three-conductor flat shielded cable, which gave values as high as 10.1 ohms in some instances. These high readings occurred because the semi-conducting compound between the shield and grounding conductors in the flat cable was a relatively high-resistance material. Cable manufacturers are continuing research in this area to develop semi-conducting compounds with lower resistances.

The test results revealed different findings for round SH-C cables, because some very high-resistance readings exceeding 100 K ohms were observed. In one cable, grounding conductor-to-shield contact was inadequate because filler material was not laid under the ground conductors to bring them to the outside perimeter of the conductor assembly. In another cable sample, a fabric semiconductive tape had been wound over the phase- and grounding-conductor assembly, partially insulating it from the shield.

These tests point out the importance of proper cable design. Specifically, a low-resistance path must exist between the shield and the grounding conductor along the entire length of the cable. Low resistance between

grounding conductor and shield is necessary to prevent the shield from becoming energized between two unshielded splices. Therefore, the round SH-D cable is the best design since the ground conductor is in intimate contact with the shield. The use of fillers under the grounding conductors to push them against the shield in SH-C constructions also provides intimate contact, but quality-control and flex-life problems may result.

An additional electrical test was devised to show the effects caused by a person using a metal object to penetrate an energized cable. To duplicate worst-case conditions, the ground-current-limiting resistor was eliminated from the circuit so that the current through the shield would be allowed to rise above 25 amperes.

A 218-volt ac source was used to power two series-connected 100-watt electric lights. One wire of the circuit was routed through a sample of flat SH-D cable from the test site. The six-penny nail was connected to a grounded 1,000-ohm resistor to simulate a worker, also under worst-case conditions. After the cable was energized, a remotely operated apparatus drove the nail into the cable.

Ten trials were performed and in 9 out of 10, the current flowing through the shield was sufficient to trip a 20-ampere circuit breaker in approximately 5 cycles or 83 milliseconds. The test results were very repetitive for these nine trials; identical current levels were observed in each. Current flow through the worker was a harmless 2 milliamperes, while current flow through the shield was 1,800 amperes. During the nine trials, the shield sustained no noticeable damage. However, during one attempt, the breaker was not activated because the shield around the nail-penetration area was destroyed.

A flexing machine was also used to investigate shielded cables (9). Three cable types were flexed around 10-inch sheave wheels for at least 10,000 flexures. The cable types investigated are listed as follows:

1. 2/0 AWG, three-conductor, round, type SH-D + GC, 2,000 volts.

2. 4 AWG, three-conductor, round, type SH-D - GC, 5,000 volts.

3. 6 AWG, three-conductor, round, type SH-C - GC, 2,000 volts.

No significant shield-wire breakage occurred in any of the SH-D samples; however, grounding conductors broke frequently. The shield maintained the grounding-circuit continuity when grounding conductors were damaged.

The nylon-strand member of the SH-C nylon-copper shield was damaged in places when the grounding conductor buckled (fig. 1).

In addition, another type of damage, shown in figure 1, was observed in the SH-C cable. The grounding conductors had become bent and pushed against the shield, causing shield-wire damage in a few separated locations.

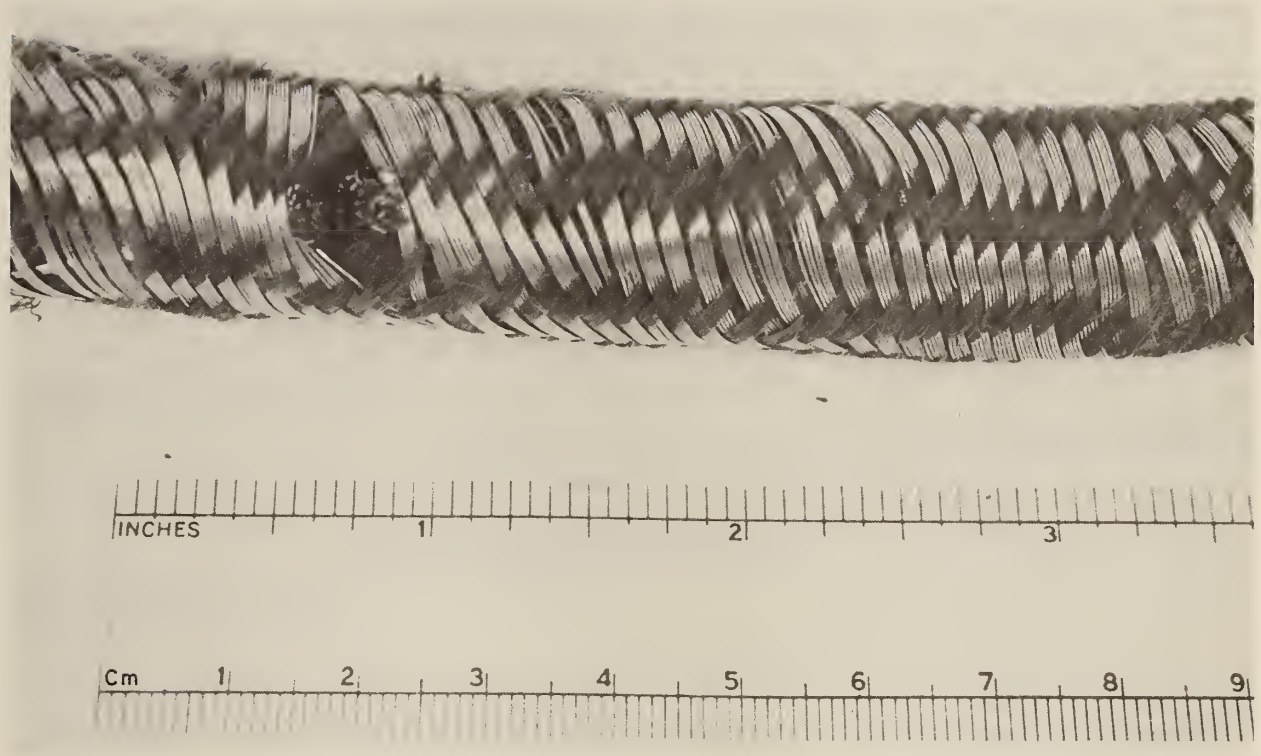

FIGURE 1. - Grounding-conductor failure caused shield separation and breakage.

Several methods of attaching a replacement shield in a splice were tested with the flexing machine. Shield samples were soldered and taped into place, and both braid tapes and tubes were used. The most flexible method was found to be an overlapped shielding tube that was held in place with rubber insulating tape.

A time study was made to determine the additional time necessary to splice a low-voltage shielded cable. An experienced splicer working aboveground in a shop was studied (8). Accordingly, the durations recorded may be faster than for an "in-mine" operation. However, a percentage of the total time used to remove and replace the shield was calculated so that the additional time required could be estimated for any case. The cable was a 2/0, three-conductor, round, SH-D with a grounding conductor, 2,000 volts, and the repair shield was half-lapped metallic tape. Total elapsed time for the splice was 1 hour, 7 minutes, and 24 seconds; the time spent in removing and replacing the shield was 10 minutes, 42 seconds.

Therefore, a three-conductor SH-D cable with nylon-copper braid takes about 16 percent more time to splice than its nonshielded counterpart. Since only one shield must be replaced for an SH-C construction, the splicing time increase is only approximately 5 percent. The percentage increases for coupler installation were also about 5 percent.

UNDERGROUND INVESTIGATIONS

The feasibility of using shielded cables was pursued further by installing the cables on underground coal mine machinery and recording their performance. The SH-D construction was evaluated on a continuous miner and shuttle car at one mine, and the SH-C construction was installed on a shuttle car in another mine. Each of the cable types will be discussed separately.

SH-D Investigation

A performance comparison was made between shielded and nonshielded cables on two similar underground mine production sections. The performance comparison of the shielded versus nonshielded miner cable occurred during the period September 4, 1976, to January 6, 1977. The maintenance history of the two cables was compared; table 1 summarizes the results.

TABLE 1. - Summarized maintenance history of the SH-D and nonshielded miner cable inmine evaluation[1]

Description of maintenance action	Number of occurrences	
	Nonshielded cable	Shielded cable
Cable damage resulting in--		
Complete splices	4	2
Jacket repairs	1	0
Reentering in machine	2	3
Tripped circuit breakers (requiring repairs)	1	2
Repair of previous splice	1	0
Removal of portion of cable containing two splices	1	0
Cable pulled out of junction box and had to be reentered	1	0

[1]Some repairs were not reported since unreported repairs were present in the shielded cable at the time it was sent out of the mine.

Less frequent damage of the shielded cable resulted possibly because the mine workers took better care of the special cable. They were inclined to do so because (1) it was under investigation, (2) it was new and unknown, (3) damaged areas were harder to locate, and (4) presence of the shield made the cable more difficult to repair and resulted in longer splice times.

Researchers and mine operators believed that the performance of the SH-D continuous-miner cable was acceptable. However, miners were overanxious to get this heavier, stiffer cable out of the mine to be repaired. Consequently, it had fewer than the maximum allowable number of repairs when it was removed from service.

An SH-D and a nonshielded shuttle-car cable were also manufactured. Because the shielded, flat, three-conductor cables had never been made before, many manufacturing problems and delays were encountered. A major restraint occurred when the manufacturer produced an oversized jacket that reduced the length of cable stored on the shuttle-car reel to an unacceptable quantity.

Consequently, the cables were not put into use underground. The following problems resulted when the cable was tried on a shuttle car, operating aboveground.

1. The maximum SH-D cable storage capacity on the shuttle car reel was 320 feet; the capacity using the nonshielded cable was 590 feet.

2. Improper layering of the shielded cable on the storage reel resulted in a local buildup of cable since the spooling mechanism was designed for smaller cable diameters.

3. A binding and twisting action was evident as the SH-D cable passed through the reel guide.

4. Any increase in the size of the SH-D cable (such as splicing or mud) could have resulted in cable entanglement in the spooling guide.

5. The cable did not conform properly to the sheave-wheel shape because it contacted only the outer edges of the wheel, resulting in probable cable-jacket wear points.

6. The relatively heavy shielded cable required higher reel tension to prevent the shuttle car from running over its own cable. On the other hand, increased tensions would put greater stresses on splices.

7. The cable was generally stiff and inflexible.

However, these problems can be corrected, and a new cable is being designed and manufactured.

SH-C Investigation

The performance of SH-C cable was also compared with the performance of nonshielded cable. The study was performed in a different underground mine using three-conductor, round cables. On January 18, 1977, the SH-C cable was placed on one shuttle car in a conventional mining section and a similar nonshielded cable was installed in another car in the same section. Although there were three shuttle cars on this section, only two were included in the experiment.

As in the case of the SH-D shuttle-car cables, the first set of cables manufactured for the SH-C cable demonstration (shielded and nonshielded) project was unacceptable. Problems encountered with the first set of cables were as follows:

1. The insulation covering the phase conductors in the nonshielded cable was extruded into the wires of the phase conductors. Because of difficulties encountered in separating the insulation from the wires, poorly made and time-consuming splices could have resulted.

2. The ground-conductor stranding was different in the two cables. The grounding conductors in the nonshielded cable consisted of the herringbone lay of seven ropes of seven strands each (7 x 7), whereas the grounding conductors in the shielded cable consisted of a single bunch (104 strands).

3. The ground-check wires were also constructed differently in the two cables. The nonshielded cable had a ground-check configuration of 7 x 33, whereas the ground-check configuration in the shielded cable was 7 x 7.

4. Furthermore, a nonconducting cloth tape was wrapped around the conductor assembly between the shield and grounding conductors, resulting in a high-resistance path between the shield and grounding conductors.

Consequently, the cables were remanufactured. The new SH-C cable did not have the cloth wrapping, and the grounding and ground-check conductors in both cables were the 104-wire construction. In addition, the insulation was not extruded into the phase conductor.

At the time the cables were installed, the cable-storage capacity of the standard shuttle-car reel (nonshielded) was approximately 500 feet. However, at the time the measurement was made, the position of the cable tie-off point limited cable-reel capacity to 300 feet. Researchers estimate that an additional 50 to 100 feet could have been stored on the reel, which would bring the total to about 425 feet. In addition to the larger size of the shielded cable, improper cable layering on the storage reel accounted for its relatively low storage capacity.

Even though cable-reel storage capacity was less, mine personnel were quite pleased with the performance of the shielded cable during the first 2 months of service. However, three problems were noticed by the operator of the shuttle car, the MSHA electrical inspector, and one of the section foremen.

Although the operator of the off-standard shuttle car was unaware that the cable was shielded, he noticed that it was not being reeled-in properly when tramming to the belt feeder. To avoid running over the cable, he was forced to tram slower and to be more cautious of the cable location, especially when tramming around pillar corners. Redesign of the spooling device to accommodate the larger diameter cable should eliminate this problem.

In another instance, the MSHA electrical inspector believed that the shield connection in splices had to be soldered, rather than taped. After much discussion, research personnel convinced him that a taped connection was safe and allowed by law.

During the latter part of the second month of the cable performance appraisal, section conditions became very muddy. Consequently, shuttle-car haulage led to the formation of ruts in the belt entry, and these harsh conditions resulted in more frequent cable failures. Because of problems in identifying faulty splices in the shielded cable, as well as longer splicing times, one of the section foremen became very displeased with the shielded cable. His crew members also voiced their dissatisfaction. The head

maintenance foreman, as well as crew members for the following shift, were questioned with regard to the aforementioned problems. However, they were not experiencing these difficulties. The head maintenance foreman indicated that the cable and splice failures were not a fault of the cable, but caused by crushing, pinching, and runovers.

Cable and splice failures continued to increase through the third month after cable installation. Finally, on April 22, 1977, after 3 months of two shifts per day, 5 days per week operation, the shielded cable was removed from service because of excessive cable-related downtime. Production on the cable was estimated to be 35,000 tons. The nonshielded cable was removed from service shortly thereafter. Soon after the cables were taken out of the mine, the head maintenance foreman was interviewed. The following problems, which were associated exclusively with the shielded cable, were discussed in detail.

1. Conductor connections in splices were made by crimping a long butt-connector on the conductors. Occasionally, the crimping action resulted in sharp or pointed connector ends. As the cable was flexed, the connector end pierced the insulation and contacted the shield, which tripped the circuit breaker. The mine used a different connection method on their regular nonshielded cables.

2. Cables were occasionally run over and crushed, but the damage did not cause immediate tripping. Later, damaged insulation allowed enough phase-to-ground current to trip the breaker. These leakage problems were often difficult to locate, and they resulted in considerable downtime.

3. Splice failures occasionally caused high-resistance faults to the shield. As in item 2, the failed splice was difficult to identify. Consequently, repairmen occasionally replaced several cable splices before they found the faulty one.

At the time the shielded cable was removed, it contained eight permanent splices. All splice jackets were of the heat-shrinkable type. In addition, the shielding was replaced correctly on every splice examined, and the tape-wrap method of securing the shield work effectively. Some of the conductors were connected with crimp connectors and others were simply tied together. The two types of insulation used were heat-shrinkable tubing and tape. In several instances, the two grounding conductors were connected together with one connection. Another interesting observation was that the ground-check conductor connections were not insulated in several of the splices. Since the shield was in contact with the uninsulated ground-check conductor connections, a short circuit existed in the ground-monitor circuit. The grounding circuit could have been opened inby the short, but the ground-check monitor would not have detected it. This dangerous practice was apparent in both shielded and nonshielded cables.

In addition to the splice examination, portions of unspliced cable were removed and inspected. One type of shield failure found was very similar to those witnessed in the laboratory where grounding conductor breakage caused shield wires to break and separate.

Two other instances of shield failure occurred that were not caused by grounding-conductor breakage. Jacket damage was not obvious, but the entire shield circumference was damaged for approximately 4 inches in both areas. In addition to localized shield failures, conductor insulation was also damaged. Because of the absence of jacket damage, researchers suspect that the cable was crushed.

Although copper shield wires remained intact, they bunched together and allowed uncovered areas to develop as shown in figure 1. The bunching resulted when the nylon threads abraded and parted as they rubbed against metallic components in the cable, such as the grounding conductor. Again, this damage was a local occurrence. Consequently, it was obvious that an extremely abrasion-resistant nylon strand was necessary.

Based on cable downtime statistics kept by maintenance personnel, the average time per repair occurrence for the nonshielded cable was 35.8 minutes. The average repair time calculated for the shielded cable was 40.5 minutes or 11.7 percent more than for the nonshielded cable. Eighteen downtime incidents were reported for the shielded and 23 for the nonshielded cable.

Despite the fact that there were several problems with the SH-C cable, mine personnel were very pleased with the performance. This results primarily from the fact that the cable lasted as long or longer than most nonshielded cables. As a result, mine personnel agreed to reinstall both the shielded and nonshielded cables after they were welded and vulcanized in a local cable-repair shop.

CONCLUSIONS

Conclusions that were drawn from the investigation to date are listed according to the sequence of parameters that was presented at the beginning of this paper.

Electrical Shock-Hazard Protection

Accident analysis and literature review work indicated that the introduction of shielded low-voltage cables has potential for hazard reduction. However, the shield must have adequate coverage and a low-resistance contact between the shield and grounding conductor. The grounding conductor and the shield should be continuous through splices, and the protective devices in the load center must be operating properly.

Currents Induced in Grounding Conductors

Shielded cables have the potential for induced ground currents when the cable cross section is unsymmetrical, for example with type SH-D-GC cables. The induced current potential is not present when the cable is symmetrical, such as the type SH-D + GC cables.

Ground System Integrity

Shielding improves the grounding system. For example, if a break occurs in a grounding conductor, the grounding circuit remains continuous provided there is a low-resistance path to the shield. Again, the importance of replacing the shield in splices must be stressed.

Maintenance Testing

On the one hand, shielding facilitates nondestructive dielectric strength testing since it provides a grounding medium around the conductor insulation (SH-D) or conductor assembly (SH-C). On the other hand, locating faults in low-voltage portable cables is more difficult because the easily recognized symptoms of a cable "blow-out" are not present with the more sensitive shielded cable. Power is usually interrupted before noticeable cable damage occurs.

Purchasing and Operating Costs

Purchasing costs were estimated to be 10 to 20 percent higher for shielded cables; however, purchases for experimental purposes were considerably more expensive. Operating costs would increase because of increased time for splicing and increased splicing kit costs (approximately $1.50 for an SH-D splice kit).

Availability From Manufacturers

Initially, a wide range of low-voltage shielded cables would not be available. Some cable manufacturers indicated that a 1- to 2-year tool-up period would be necessary. Others did not anticipate an extensive problem.

Flexibility

Laboratory and inmine testing have shown that shields can withstand the rigors of bending around sheave wheels and reels better than the present grounding conductors.

Splicing and Coupler Installation

The best method of replacing the shield in a splice is a braided tube that can be slid over the completed joint. Using a braided tape, the splicing time for a three-conductor SH-D cable was increased by 16 percent. SH-C splicing time would be increased by an estimated 5 percent. Taping the overlapped shield produced better flexibility than soldering.

Outside Diameter

The outside diameters of shielded cables are larger; therefore, the length of cable that can be stored on a reel is reduced. Underground investigations showed that, in one instance, shuttle-car reel capacity was reduced to 320 feet from 590 feet with an SH-D cable, and in another instance, to 425 feet

from 500 feet with an SH-C cable. In addition, cable-entrance or packing glands and splice-kit jackets must be changed when a shielded cable replaces a nonshielded one.

Stiffness and Weight

Shielded cables, especially when they are new, are stiffer than their nonshielded counterparts. They are also heavier. Consequently, higher reeling tensions are required and the cables are harder to handle. Furthermore, additional freight charges add to the cost of shielded cables.

Nuisance Tripping of Circuit Breakers

A shielded cable will not trip a circuit breaker unnecessarily, but it is more sensitive to a damaged or hazardous area. For example, if a hole exists in the outer jacket of a nonshielded cable, the power will probably not be interrupted; it would be interrupted with a shielded cable.

Cable Construction

Obtaining a proper shielded-cable design is extremely important. Outside diameter, flexibility, grounding-path resistance, and other important parameters depend on the cable design. As previously mentioned, the shield must cover adequately the phase-conductor insulation or assembly, and a very low resistance path to the grounding conductor is necessary. In addition, the physical strength of the nylon in a nylon-copper shielding braid must be sufficient for the flexing and tensile stresses impressed on the cable. Furthermore, outside diameter dimensions must be minimized to allow a maximum length of cable to be stored on shuttle-car reels.

The SH-C cable construction compares favorably with the SH-D in some of these parameters and unfavorably in others. For example, the SH-C is lighter, more flexible, smaller in outside diameter, and easier to splice. However, it must be constructed so that a low-resistance path exists between the shield and grounding conductor, which is difficult to accomplish. In addition, the SH-C cable is not as sensitive to phase-to-phase leakage currents and faults as is the SH-D. Therefore, considering present manufacturing techniques, the SH-D is safer and easier to manufacture properly, while the SH-C has several user-oriented advantages.

RECOMMENDATIONS

The following recommendations are made:

1. A fault-locating device should be developed for low-voltage, shielded cables that is simple to use, reliable for locating opens and shorts, rugged enough to withstand the mine environment, MSHA- and State-approved, and inexpensive.

2. Equipment-reel and spooling-device designs should be modified to accommodate the larger physical size of shielded cables.

3. An in-depth study of low-voltage shielded-cable design is necessary. The study should include design, manufacture, and laboratory testing of several varied parameters. Improvements may be necessary in angle of braid, size and hardness of wire, size and strength of nylon, and ground-wire contact points in both SH-C and SH-D designs. Innovative manufacturing processes, such as wrapping a braided metallic tape over conductor insulation (which would increase production rate and decrease cost), should be investigated. Innovative cable designs including new materials such as "conducting rubber," should be studied to reduce cost and improve flex life.

4. Splice kit manufacturers should develop kits with instructions for removing and replacing the shield, shield replacement sleeves, and properly dimensioned jackets.

5. A time period of at least 1 year is necessary to allow cable manufacturers and suppliers to "tool-up," train people, and develop required warehouse inventories. In addition, mine operators must have adequate time to gradually replace the cables currently in use.

REFERENCES

1. Canadian Standards Association. Canadian Electrical Code Part V, Use of Electricity in Mines, CSA Standard C22.5-1971, November 1971, 36 pp.

2. Cartwright, J. Department of Mines and Petroleum Resources, Victoria, British Columbia, Canada. Private communication, 1974. Available upon request from R. H. King, Pennsylvania State University, University Park, Pa.

3. Coal Age. Wider Use Of Shielded Cable Underground Probable As Critical Problems Are Solved. V. 79, August 1974, pp. 90-91.

4. Dornetto, L. D. The Importance of Grounding Systems in the Protection of Personnel and Equipment. BuMines IC 8694, 1975, 114 pp.

5. Fesak, G. U.S. Department of Labor, MSHA, Arlington, Va. Private communication, March 1976. Available upon request from R. H. King, Pennsylvania State University, University Park, Pa.

6. Hansen, T. E. A Study of Induced Voltage in Grounding Conductors of Mining Cables. Min. Cong. J., v. 59, May 1972, pp. 25-29.

7. Hilliard, F. W. McIntyne Porcupine Mines Limited, Coal Division, Grande Cache, Alberta, Canada. Private communication, November 1974. Available upon request from R. H. King, Pennsylvania State University, University Park, Pa.

8. Kadyk, B., Jr. J-H Service Company, Indianola, Pa. Private communication, February, 1975. Available upon request from R. H. King, Pennsylvania State University, University Park, Pa.

9. King, R. H. Underground Coal Mine Trailing Cable Splices. M.S. Thesis, Pa. State Univ., University Park, Pa., June 1974, pp. 21-26.

10. Mason, W. A. U.S. Department of Labor, MSHA Health and Safety Analysis Center, Denver, Colo. Private communication, April 1975. Available upon request from R. H. King, Pennsylvania State University, University Park, Pa.

11. Molinski, A. E. Effects of Electricity on the Human Body. Min. Cong. J., v. 56, July 1970, pp. 64-68.

12. Sopko, P. A. Shielded Low-Voltage Trailing Cables for Underground Coal Mines. M.S. Thesis, Pa. State Univ., University Park, Pa., March 1977, p. 86.

13. Stanek, K. West Virginia University, Morgantown, W. Va. Private communication, October 1976. Available upon request from R. H. King, Pennsylvania State University, University Park, Pa.

LOCATING TRAILING-CABLE FAULTS USING AUTOMATED TIME-DOMAIN REFLECTOMETRY

by

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ABSTRACT

Time-domain reflectometry has long been an accepted and used method for locating electrical faults in electrical cables. The process has, however, required the use of equipment that is somewhat complex and difficult to use. The skill level needed to operate such equipment is high. Therefore, the use of the time-domain reflectometry process has been limited to selected locations and controlled environments. The process, however, has great potential for mine system applications. The ability to locate and repair trailing power cable without removing it from the mine would result in great savings in cost and employee-hours. Therefore, an automatic microprocessor-controlled time-domain reflectometry system was developed to reduce process complexity and skill level needed to operate the unit. The theory of operations is discussed along with the computer analogies used in the unit. The present unit capabilities are presented and future areas of application and research are discussed.

INTRODUCTION

Electrical faults can occur in the trailing electrical cables used by mining equipment that can prevent the use of the cables until appropriate repairs are made. These faults can appear in several forms: shorts between conductors, open circuits, or resistive faults. Many times short circuits result in irrefutable evidence of fault location, but open circuits and resistive faults may not produce any superficial damage that can be used to pinpoint the fault location. The faults that produce very few clues regarding their location must be found by other means. Some methods cause further damage to the cable; others may artificially correct the problem only to have it recur. Time-domain reflectometry, however, exhibits the potential to describe accurately the location of each significant fault and its relative magnitude so that correct repairs can be made.

Time-domain reflectometry (TDR) (1, 3)[4] is a process, similar to radar, which makes use of electrical pulses and their reflections to measure distances to anomalies in electrical cables. The process is not new; it has been

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used for many years by persons interested in determining distances to faults in electrical cables. The National Aeronautics and Space Administration (NASA), for example, has made extensive use of TDR (4) to determine the location of electrical faults in the tens of miles of wires used around its space launch complexes. The TDR method allows NASA to locate electrical faults much more rapidly than other search techniques and permits repairs to be made during very tight launch time frames.

TIME-DOMAIN REFLECTOMETRY

All electrical cables have associated with their physical structure and material makeup certain characteristic properties that can be used to identify each cable. One of these properties, which is independent of cable length, is referred to as the "characteristic impedance--Zo"; that is, television antenna wire is referred to as 300-ohm twin lead, where Zo equals 300 ohms. Another property is the cable phase velocity, which is an indication of how fast an electrical impulse will propagate along the cable. In other words, it takes a finite amount of time for an electrical signal to get from one end of a cable to the other. Therefore, an electrical pulse will propagate along a cable at a velocity equal to the phase velocity as long as the characteristic impedance of the cable is unchanged. Any electrical fault in the cable will cause a localized change in the characteristic impedance of the cable. This localized change will, in turn, cause the electrical pulse to be somewhat reflected back to the sending point. The magnitude and polarity of the reflection will be dependent upon the nature of the impedance change. Impedances greater than the characteristic impedance will cause positive reflections between 0 and 1 times the original signal voltage, which then adds to the original signal voltage; impedance less than the characteristic impedance will cause negative reflections, which subtract from the original signal. These physical properties along with the reflection property are utilized in the TDR process.

The usual method employed when using the TDR process is to apply a voltage pulse to one end of an electrical cable and to observe how this voltage is changed due to reflections from electrical faults (fig. 1). The voltage is displayed on an oscilloscope so that time measurement can be made on the waveform of the voltage and distances can be calculated. A typical TDR waveform is shown in figure 2. This waveform results from a nonfaulted cable that has its far end open circuited. Notice that the first voltage increase in the waveform occurs whenever the initial pulse is applied to the cable. The second increase is due to the reflection voltage from the open-circuited far end returning to the sending end. The time it takes for the reflected waveform to return to the sending end is related to the phase velocity of the cable and the cable length. Knowing the phase velocity and reading the time measurement from the oscilloscope, the length of the cable can be calculated using the following formula. The factor of 2 in this formula results from the waveform traveling down the cable and back:

$$d = \frac{v_p \cdot t}{2} .$$

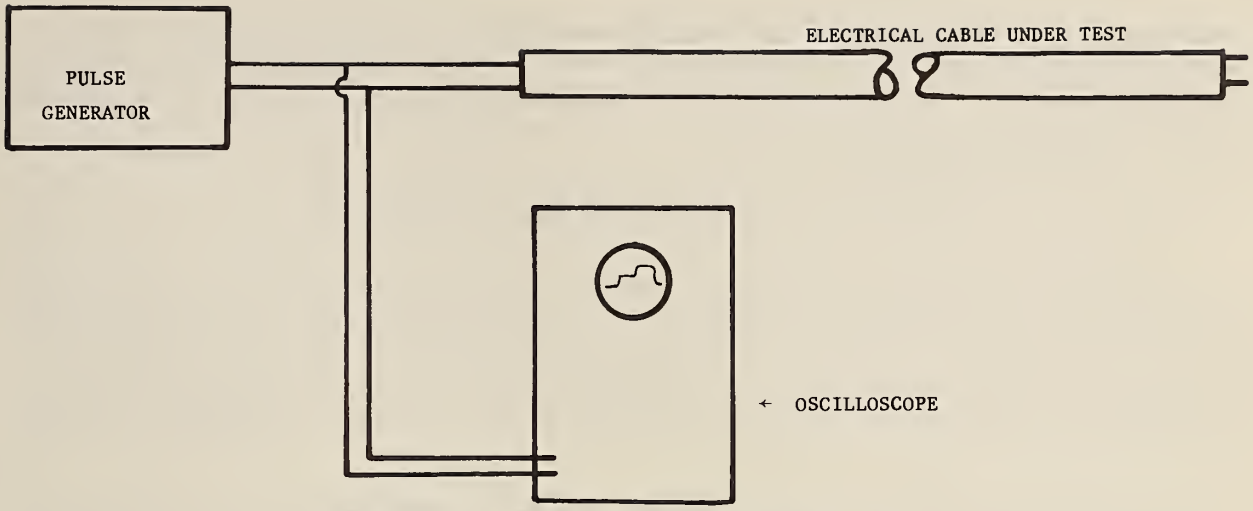

FIGURE 1. - Typical TDR equipment setup.

The use of the previously described TDR system requires a fair amount of skill and knowledge. The person using the system must (1) be able to match the internal impedance of the pulse supply to the cable impedance, (2) Understand how to use an oscilloscope and be able to use it to make accurate time measurements, and (3) know the phase velocity of the cable under test and be able to use the time measurements in the formula to calculate distance. The process is further complicated by the fact that any cable fault will produce other reflections that must also be interpreted. The procedure is difficult, and the equipment needed is complex. The complexity of the process and equipment make the TDR procedure an unlikely candidate for mine use, but with some modification, the TDR procedure could be a very useful tool in a mine environment.

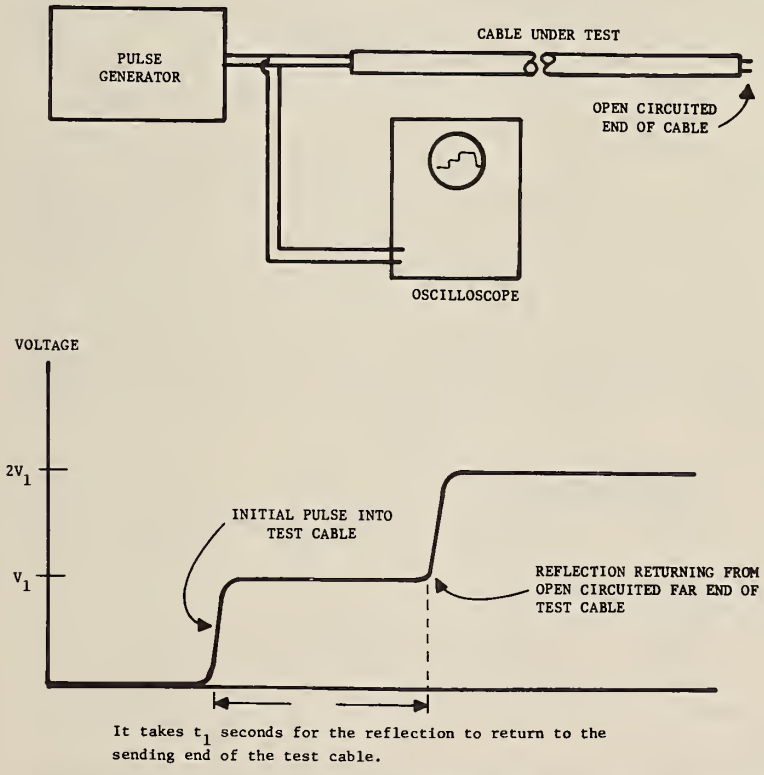

FIGURE 2. - TDR waveform where the sample cable has no faults and its end not connected.

The project that Carnegie-Mellon University has undertaken was to modify this TDR process into one that is simple. The modification has been accomplished by the addition of a microprocessor unit to the TDR equipment. The microcomputer

performs all of the analysis of the TDR waveform and displays the relative magnitude of the electrical fault and its distance down the cable on a simple numerical display. This modification eliminates the need for an oscilloscope. The user can read the fault distance from the display, measure this off on the cable, and effect repairs.

THE AUTOMATIC TIME-DOMAIN REFLECTOMETRY UNIT

The automatic TDR unit is designed around a microprocessor unit that will automatically interpret the TDR waveforms. The computer by itself cannot perform any analysis on a TDR waveform unless this waveform is first stored digitally in the computer memory. Therefore, several other units must work in conjunction with the computer to accomplish this analysis. The block diagram of these units is shown in figure 3.

The pulse generator and timing unit are critical elements. The TDR information regarding the cable is contained within an extremely small time frame, typical pulses being between 200 and 400 nanoseconds, which is less than 1 one-millionth of a second. Therefore, any errors in timing can cause gross inaccuracies in the analysis. The sampling circuit, the sample and hold, and the analog to digital converter are used to convert the analog TDR pulse to digital code in an orderly fashion. The present unit makes one sample of the TDR

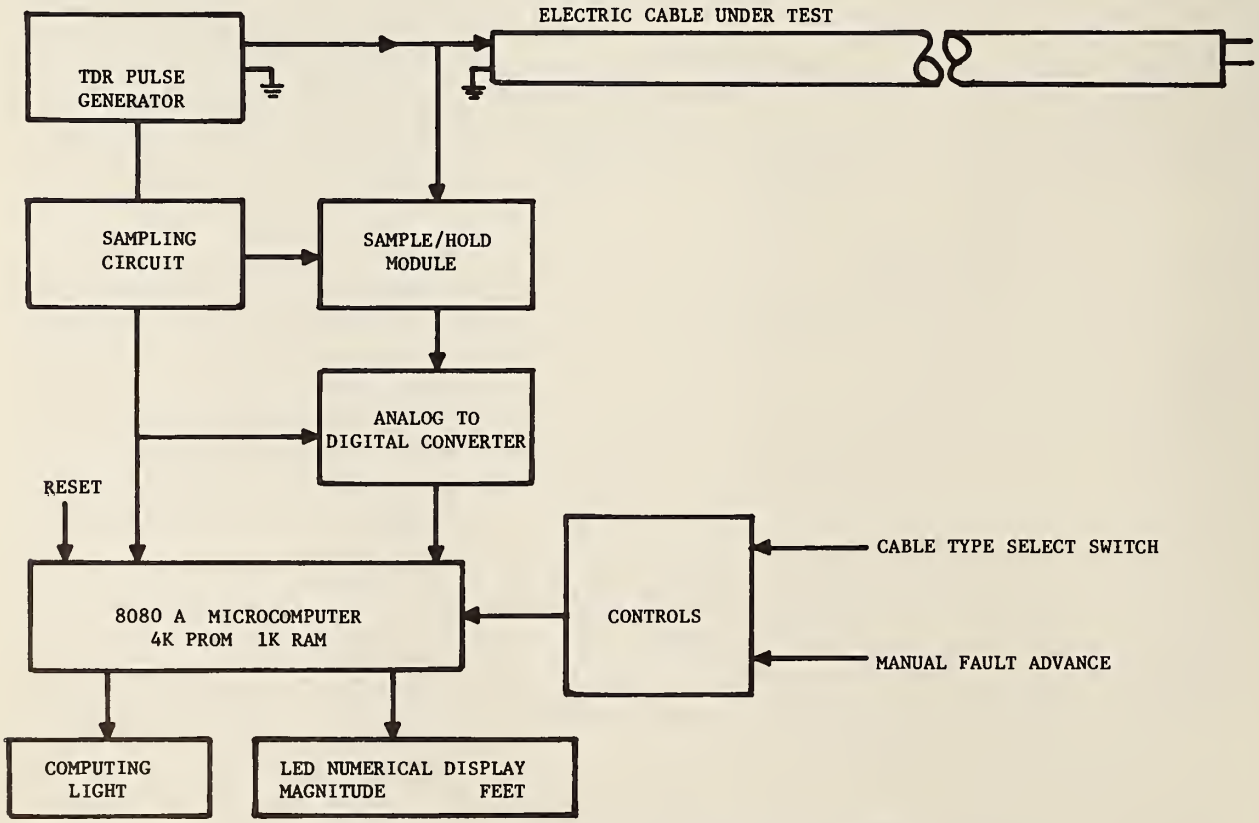

FIGURE 3. - Block diagram of automatic TDR unit.

waveform corresponding to each foot of subject cable. The microprocessor then accepts the digitized waveform and analyzes the data for possible fault locations. The faults are then displayed in increasing distances down the cable.

The pulse generator produces a 5-volt, 10-microsecond pulse every 240 microseconds. This pulse is applied to the cable, and the voltage at the sending end is monitored for returning reflections. The timing unit then selects the proper instant of time whenever a sample of the TDR waveform should be taken. Only one sample is taken from any one TDR waveform due to the time necessary to digitize and store the data. Therefore, successive samples corresponding to increasing the distance down the cable are taken from a series of the pulses. In the present unit, the maximum possible cable length is approximately 1,000 feet; therefore, 1,000 TDR pulses are sampled and the information stored.

The method used to obtain the successive samples employs two ramp generators and a voltage-comparison circuit. One ramp generator is set at a much higher frequency than the other (fig. 4). The fast ramp generator, which also produces the TDR trigger pulse, has its voltage compared with that of the slow ramp; each time the fast voltage exceeds the slow, the TDR pulse is sampled. Since the slow-ramp voltage is constantly increasing, this sample point moves across the TDR waveform, giving a different sampling point each time.

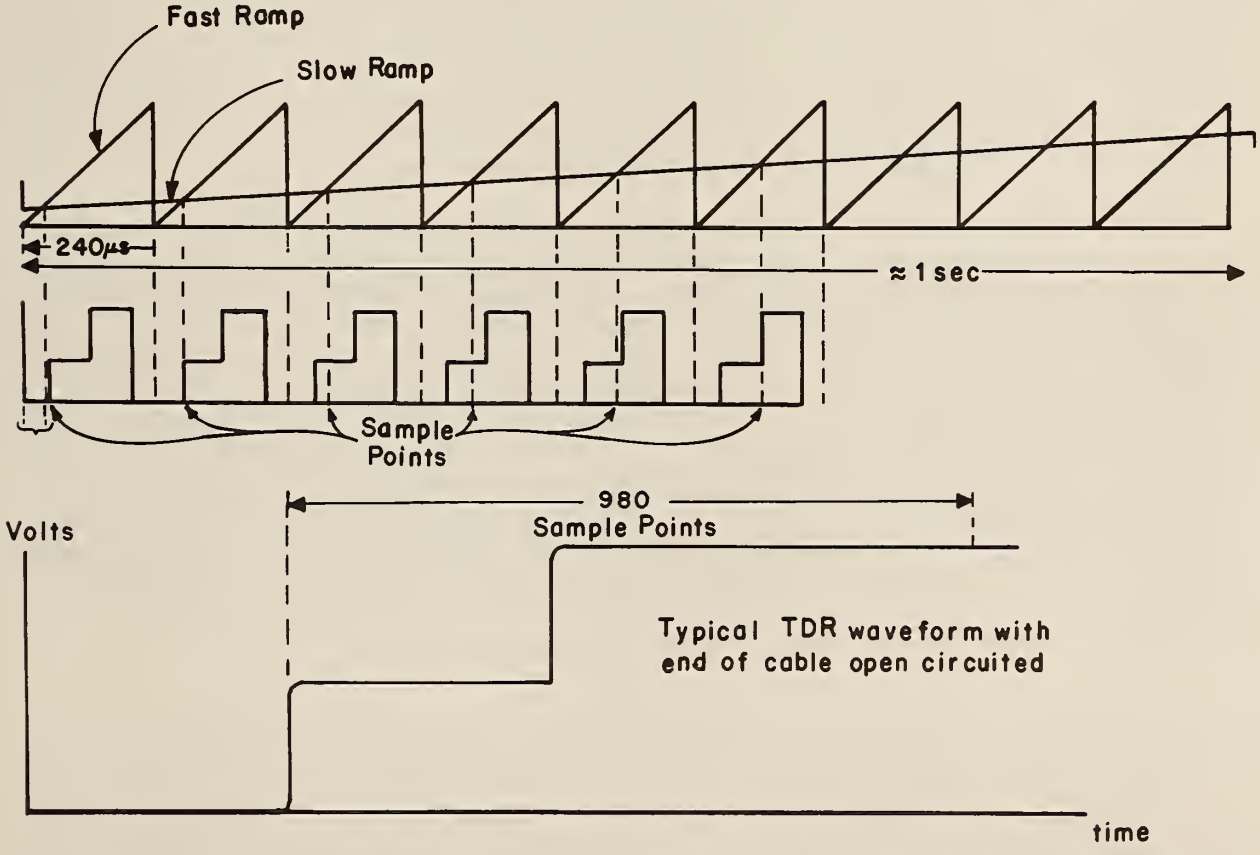

FIGURE 4. - Fast ramp and slow ramp waveforms with sample points in respective TDR pulses.

This procedure makes the assumptions that (1) over the brief sampling time scale, the TDR waveform will not change, and (2) the successive waveform sampling will provide the same information as could be gotten from a single TDR pulse. Both of these assumptions are based upon observation and appear to be reasonable. However, different cable types do have different characteristic impedances and phase velocities. Therefore, some provisions must be made for adjustment of the fast-ramp generator to make the sample points correspond to each foot of cable and to match the TDR pulse-generator impedance to the cable impedance. The present automatic TDR unit has external controls that allow the operator to adjust the device to the cable under test, but future models will be even simpler. Most mine cables fall into certain classifications with similar impedances and phase velocities. A single control with a group of settings corresponding to each of the cable types would eliminate the need for adjustments, and only require that the cable type be visually identified and the proper setting selected.

THE TDR PROGRAM ALGORITHM

The operation of the automatic TDR unit is dependent upon the programming of the microcomputer. The computer has both a static and a dynamic memory. The static memory is made up of programmable read-only memory units (PROM). This memory section contains the actual program used to store the TDR data and to determine the fault locations. The dynamic memory uses random access memory units (RAM), which are used to store the digitized TDR waveform. The present program uses 1,000 bytes of PROM for the analysis program and 1,000 bytes of RAM (each corresponding to 1 foot of cable) for TDR data storage. The computer uses the timing units, sampling units, and analog-to-digital units to store information into the RAM memory. After the memory is full the PROM program is used to analyze and display the results.

The program analyzes the data by looking for changes in TDR voltage from foot to foot in the cable. All faults produce either rises or drops in the TDR voltages and the magnitude of the rise or fall is related to the nature of the fault. The program takes the voltage difference between adjacent 1-foot segments of cable and stores this in memory. Positive charges correspond to series resistive faults; negative charges indicate shunt faults. The positive differences are indicated by illuminating one open light in the display; negatives are indicated by a short light. The fault magnitudes are scaled from 0 to 99. An open light with 99 on the display corresponds to an open circuit or infinte impedance, and a short light with 99 means short circuit or zero impedance. The ranges in between these values correspond to increasing impedances (fig. 5). The relative magnitudes displayed by the TDR unit can be related to figure 5 to obtain an approximation of the type of fault and its impedance relative to the characteristic impedance of the cable.

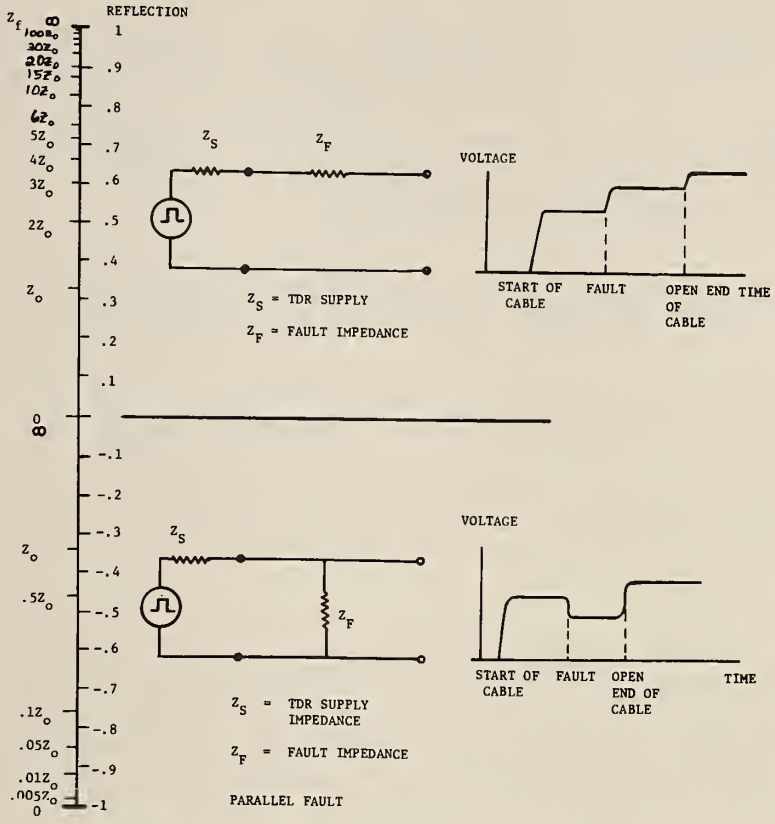

FIGURE 5. - Relationship between impedance, characteristic impedance, and the reflection coefficient.

CAPABILITIES OF THE TDR UNIT

The present TDR unit has the theoretical ability to pinpoint electrical faults to within ±1 foot. However, the unit is very susceptible to noise on the powerlines. Any noise causes errors in the timing unit, which cause further problems in TDR waveform storage. The programming appears to locate faults with good consistency using test data, but whenever the unit stores its own TDR waveforms, much accuracy is lost. The present unit now has a ±10-foot accuracy for distance measurements. How this accuracy compares with visual interpretation of TDR waveform will be determined in field trials. Limited field testing indicates that a 30-ohm series fault and a 300-ohm shunt fault are detectable, but this also must be verified further.

The present unit can be combined with a cable-signaling method to pinpoint faults. The TDR unit could be used to indicate the general location of the cable fault. Then, an audio-frequency signal could be applied to the cable and detector readings taken in the area indicated by the TDR unit. The audio signal would change at the location of the fault, pinpointing the trouble.

The TDR system, therefore, can greatly reduce the time it takes to repair faulty cable. It also can eliminate the need to remove many bad cables from the mines for repair by making inmine repairs possible. The methodology for using the unit is simple; most people can learn to use the unit within several hours, thereby eliminating long training periods.

FUTURE TDR APPLICATIONS AND RESEARCH

The obvious area of future study is that of improving the accuracy of the present fault location unit and fault magnitude sensitivity. Several possibilities exist that can improve accuracy, such as improved power supplies to reduce or eliminate timing problems, advanced analog-to-digital converters to more accurately reproduce the TDR waveform, and additional memory to allow for finer sampling.

An interesting future application could be in preventive maintenance. The TDR unit could be used on a weekly or monthly basis to test cable for potential hazards. A history of all cables could be maintained and constantly updated based upon the new tests. All changes in the cable could be easily noted and corrective action taken prior to an electrical fault. Comparison techniques have been investigated (2) and the feasibility of the approach proven; therefore, this procedure should prove successful.

Another application might be to use the unit to monitor entire power distribution systems, again, keeping records about past TDR waveforms and noting all changes. The changes indicate areas that should be investigated for potential problems.

Additional research and program changes are also possible that could greatly improve accuracy of the unit. The possibility exists for looking at the TDR waveform between several wires in a single cable at one time or in succession. The program could be modified to analyze these waveforms and make cross comparisons to finally indicate exactly which wire may be the cause of the problem.

The present program also does not consider the problem of multiple reflections from one fault to another. These reflections can cause nonexistent faults to appear in the final display. There is a possibility that, by modifying the present program to computer enhance the data, multiple reflections can be screened out. This process could greatly improve the accuracy and reliability of the TDR unit in mine applications.

CONCLUSIONS

The addition of a microprocessor to the TDR procedure has added another degree of sophistication to the process but not complexity. The microprocessor can greatly reduce the skill level needed to make use of the TDR process and, in fact, can bring it into areas where it could not otherwise have been applied. There are many different ways to apply this automated TDR unit, and there are undoubtedly many other applications still waiting to be found.

REFERENCES

1. Herding, R. Use Pulse Instead of CW Signal. Electronic Design, May 24, 1974, pp. 60-67.

2. MacKay, N. A. M., and S. R. Penstone. A High Sensitivity, Narrow Band-Time Domain Reflectometer. IEEE Trans. on Instruments and Measures, v. IM-23, No. 22, June 1974, pp. 155-158.

3. Metzger, G., and J. Vobre. Transmission Lines With Pulse Excitation. Academic Press, New York, 1969, pp. 21-71.

4. National Aeronautics and Space Administration. Time-Domain Reflectometry for Cable-Fault Isolation. NASA Tech. Briefs, KSC-10741, v. 1, No. 3, 9 pp.

MEDIUM- AND HIGH-VOLTAGE TRAILING-CABLE SPLICE AND COUPLER CONSIDERATIONS

by

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ABSTRACT

This is a report on an investigation performed during Contract No. H0166069 "High and Medium Voltage Trailing Cable Splices and Connections," which presents a summary of the requirements formulated. The requirements are presented in the form of considerations for medium-voltage splices, and medium- and high-voltage couplers used in underground coal mines.

INTRODUCTION

The considerations outlined in this report concentrate in the electrical insulation system of splices and couplers for trailing cables in the medium (661 to 1,000 volts) and high (1,001 to 7,200 volts) voltage ranges. The application considered was for underground coal mines. The considerations are the result of surveys of coal mine personnel and equipment suppliers, examination of actual splices and couplers, and development of general requirements in each area. The main purpose of the considerations is to make present and future splices and couplers safer, more reliable, and easier to use. In the case of couplers, the considerations were generated with the hope of encouraging greater use of couplers on trailing cables. Considerations for high-voltage couplers are presented even though there are few applications at present due to the greater need for a safely operating coupler and the difficulty of splicing a high-voltage trailing cable.

During our surveys, the reason most often given for splice and coupler failure was poor workmanship due to lack of worker training and poor worker attitudes. The second reason was poor material or equipment performance. The considerations given in this report deal with the performance aspect of the splice and coupler application and would affect only what is taught in a training program. Our primary concern is that these considerations will provide mining engineers and enforcement personnel with a framework for reasonable guidelines and regulations for the construction and use of trailing cable splices and couplers.

STUDY CONCLUSIONS

These conclusions are based on our survey of various personnel, splice and coupler examinations, mine visits, and personnel observation and study.

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Medium-Voltage Splices

In our investigation on splice kit and repair shop splices on trailing cables, a study was made of the process of reinsulating, reshielding, and rejacketing the power and ground conductors that had already been rejoined with some type of compression or welded connection. Nearly all of the medium-voltage splices examined were on round SHD-GC cable, which is most often dragged behind a continuous miner. The approach used in studying the splicing process was broad and qualitative. The following are some of the conclusions:

1. The primary problem with applying splice kits in the mine is poor workmanship due to lack of training and lack of concern for safety. The secondary problem is lack of definition of what the material performance should be.

2. The present situation on splicing is poor, where a majority of low- and medium-voltage splices examined were in poor condition even though they had not failed, and represented a potential hazard with continued use.

3. To achieve improvements in the current splicing situation, splices applied to trailing cables must be (1) properly inspected to detect the flaws in assembly, (2) made of materials capable of performing according to a defined set of specifications, (3) assembled by properly trained personnel.

4. Types of splices used on trailing cable should be designated as emergency, temporary, and permanent, where an emergency splice is any insulated device to prevent a fault until a hazardous situation has been alleviated, a temporary splice is a splice made from an approved splice kit, and a permanent splice is a shop applied vulcanized or molded splice. The terminology used to describe splices should reflect reality.

Medium- and High-Voltage Couplers

During our study, information was gathered regarding the problems currently being encountered and the environmental conditions to which a medium- or high-voltage coupler used in a working section of an underground coal mine would be subjected. A study was also made of the electrical insulation system of existing high-voltage couplers to determine if the metallic shell on couplers currently required by CFR part 75.805 could be modified. The following are conclusions based on the study:

1. As voltage increases, the need for a trailing cable coupler increases because cable damage repair becomes more difficult underground.

2. The occurrence of cable damage to a 600-foot dragged trailing cable is concentrated in the first 50 to 100 feet of cable from the machine demonstrates a clear need for an in-line coupler.

3. The use of trailing-cable couplers for quick cable change-out is very attractive to underground coal mine operators.

4. The present use of trailing-cable couplers at the machine and in-line is not widespread due to size, weight, moisture, and contamination problems.

5. There is a lack of uniform set of requirements for trailing cable couplers.

6. Safe coupler operation, which can be demonstrated by required testing, is a prime consideration for getting a device to be accepted in the mine.

7. With modifications, some of the requirements from medium-voltage couplers could be considered for applicability to low-voltage trailing-cable couplers.

8. CFR 30, Part 75.805 could be revised as follows: Coupler housings may be constructed of materials other than metal provided that each phase conductor is continuously and adequately shielded with a metallic shield within the coupler housing.

9. According to our limited study, it may not be practical to have continuous metallic shielding surrounding each phase of a medium- or low-voltage coupler. Therefore, elimination of the metallic shell on existing low- and medium-voltage couplers may not be desirable unless new designs are developed.

10. The present protective-cover methods for excluding contamination from insulating surfaces in a disconnected trailing cable coupler are inadequate.

SPLICE AND COUPLER CONSIDERATIONS

The splice and coupler considerations are recommended to meet the operator's need to have a reliable, long-lasting, and safe trailing-cable splice or coupler connection that minimizes downtime. These considerations are also recommended for use as a basis for future safety regulations.

Medium-Voltage Splice Considerations

The considerations would be promoted by mine operators, kit suppliers, and repair shops as acceptable ways of inspecting splices, requiring certain material performance, and training personnel.

The most significant splicing considerations determined from our study are described in the following sections.

Splice Inspection

Jacket-Bond Test Program

An electronic technique for checking jacket bonds should be developed and built. There is also a need to establish reasonable inspection intervals that

take into account frequency of cable damage, cable function, typical splice jacket life, and other factors of a working section in the mine.

Until such equipment is developed, the bonding of the splice kit jacket should be inspected by various visual means or by attempting to insert a knife blade or a specially prepared tool between the splice kit jacket and the cable jacket at both ends as shown in figure 1. If the knife blade can be inserted 2 inches or more, the jacket bond should be considered incomplete and the jacket replaced. For jackets that consist of one layer of material, the 2-inch distance should be measured from the start or end of the layer. For jackets that consist of two layers, the 2-inch distance should be measured from the start at the thick point of the two layers. Taping the ends of a splice jacket should not be considered a sufficient means of bonding a splice kit jacket.

The inspection should be performed as often as possible while the cable is deenergized by whatever means.

Maximum Number of Splice Kits

Each mine or company would fix the maximum number of splices a cable length must have to be sent to a repair shop. This number should be dependent on the cable function. Suggested maximums might include 10 to 15 for reeled cable, and 5 for dragged cable. The purpose of this would be to accumulate experience on setting reasonable limits on the number of allowable splices. This would not apply to the State of Pennsylvania, for example, which currently allows only five splices.

In the future, some data on the life of splice kits that are applied properly and improperly need to be gathered. From such data, the average life of splice kits could be established, and with information on damage frequency, a maximum number of allowable splices on a cable could be established. Also, an investigation might be undertaken to determine splice kit costs versus shop splice costs, which takes into account downtime and cable handling.

Proof Test Voltage Levels for Shop Splices

Shielded medium voltage cables (661 to 1,000 volts) spliced in a repair shop would be tested to a minimum of 12-kV-dc dielectric withstand which is approximately 50 percent of factory test voltages for new cable. The voltage should be applied in three steps and held at the last step for 5 minutes. The leakage current should be allowed to stabilize at each step, and be recorded for a test report to be supplied with the cable. If the leakage current can not be stabilized, the cause should be determined before the cable is put into service. Future work in this area includes increasing and expanding of the voltage levels for the various types of cable and conductor sizes. Additional work also needs to be done in these areas: (1) duration of test voltage application, (2) cable terminations to be used during a test, (3) acceptable leakage current levels, (4) fault detection if a failure occurs, (5) distinctions for shielded and nonshielded medium-voltage cable, and (6) safety and training of personnel performing the tests. All of this must be considered in the process of expanding direct-current voltage proof testing at the repair shop.

FIGURE 1. - Suggested knife blade insertion test to determine adequacy of the jacket bond. *A*, Knife blade insertion indicates poor jacket bond; *B*, knife blade insertion indicates adequate bond. Tape on the blade indicates the 2-inch depth.

Splice Material Performance

Conductor Strand Binding

To reduce the possibility of loose conductor strands penetrating the splice insulation and causing a potential shock hazard or failure, protective layers of glass cloth tape are applied over the bare conductor to bind down any broken, loose, or cut strands. The glass cloth tape ties down the conductor ends of a lap splice connection and prevents protrusion of any wire strands that are cut when the insulation is stripped or that break when the cable flexes. The glass cloth may be used on butt, lap, crowsfoot, and other types of connections where the insulation is stripped back and the conductor is left bare after the crimp-on connector is installed. Figure 2 shows the application of the tape.

Glass tape suitable for this application is available in 1/2-inch width from various suppliers. At least one splice kit supplier includes this tape in the kit package. The tape can be requested to be included with whatever splice kit is presently being used.

Hand Cleansing Materials

At least 1 ounce of liquid hand cleaner and 1.5 square feet of wiping cloths should be supplied with a splice kit for cleaning the hands before and after application of the kit. Since the splicer must handle the cable, this is an important consideration when using adhesives. The adhesive bond is very sensitive to dirt and other contamination.

Insulation Water Exclusion

The power conductor and ground check wire insulation or combination of such materials should be capable of excluding water from entering the conductor area.

The insulation should perform the same function as the splice kit jacket. For example, this could be accomplished where a split sleeve is placed over the power conductors and then the sleeve and cable insulation are coated with a cement and finally wrapped with a self-vulcanizing tape. This is already accomplished with heat-shrink kits and some cold-splice kits. This procedure should apply to all kits.

Splice Personnel Training

Splice Kit Instruction Sheets

One sheet of instructions should be enclosed with a splice kit which clearly outlines the procedures employed to apply the splice kit to the cables for which it is intended.

1. Each diagram or photograph that demonstrates a procedure that requires the use of the hands should show the hands in the normal position required to perform the operation.

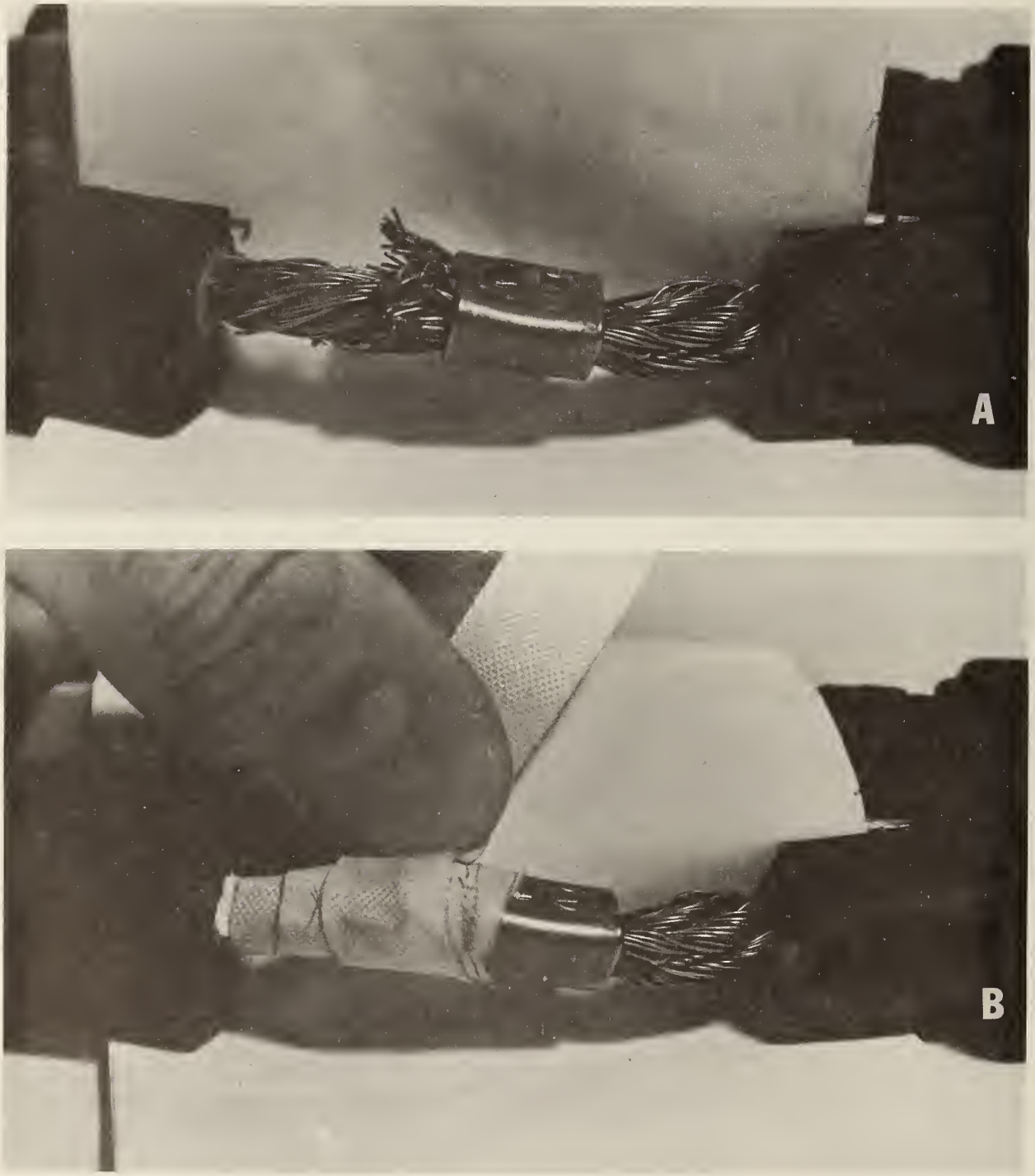


FIGURE 2. - Conductor strand binding to prevent insulation failures. *A*, Lap-type joint with protruding strands, which penetrate the insulation; *B*, binding conductor strands with glass cloth tape.

2. The application of the splice kit should be shown by separate photographs or diagrams demonstrating the application of each item supplied in the kit. There must be at least as many photographs or diagrams as there are items in the kit, with the exclusion of cleaning and abrading materials.

3. Each object in the kit should be labeled with the descriptive name used in the instruction sheet. Each individual object must be labeled on its container or on the object.

4. The instruction sheet should include a full-size drawing or template of each type of cable for which the splice kit is intended. The drawing should show conductor-cutting locations; insulation stripping lengths for lap, crowsfoot, and butt connections; shield-stripping locations; jacket-cleaning and abrasion locations; jacket removal lengths; and any other special cable preparation. If the lengths are specified, measuring devices should be provided. Examination of this drawing would be listed as step 1 on the instruction sheet.

5. All lettering on the instruction sheet should be at least pica or 11-point type.

6. All written instructions should be in plain language and simple sentences.

Splice Kit Training

Each manufacturer of a splice kit should be encouraged to provide a training manual. The training manual should describe the instruction sheet, present the rationale for each step of the splicing procedure, give warnings, and indicate difficulties. The training manual will be used for classroom instruction.

A training manual should also be available to any mine operator for the purpose of conducting his own training program. Also, mine operators should be encouraged to utilize the training programs some manufacturers or suppliers already offer.

Future Splice Considerations

Future considerations that require further development include the following:

1. Metallic shield continuity inspection program.
2. Repair shop specifications.
3. Repair shop quality control of jackets.
4. Repair shop fault location.
5. Minimum application and operating temperature of splice kits.
6. Connector-crimping, systems-flexing.

7. Splice kit application and cable preparation.

8. Cable-cleaning materials.

9. Cable change-out guidelines.

In order to control splice quality, further research should include the following areas:

1. Shield continuity test.

2. Jacket bond test.

3. Certification of repair shops.

4. Splice kit manufacturer quality control tests.

5. Electrical and mechanical performance of kit and shop splices.

6. Metallic shield protection.

7. Fire properties of splices.

8. Shelf-life testing.

9. Solvents and cement stability and toxicity.

10. Training of splicers and inspectors.

Medium- and High-Voltage Coupler Considerations

The considerations for couplers are divided into safety, reliability, and human engineering aspects. The safety aspects are intended to be further researched and developed to become regulations. The reliability and human engineering aspects are intended and recommended for promotion by mine operators, coupler manufacturers, and repair shops. The most significant considerations are described in the following sections.

Coupler Safety

If a coupler is to be used on a trailing cable in the working section, it must not only operate safely, but it must fail without causing injury to those who may be nearby. The coupler must also be demonstrated as essentially fail-safe by full-scale testing. This would apply especially to medium- and high-voltage areas where fear may prevent proper utilization unless the device is clearly safe.

Phase-to-Phase Faults

No matter how the coupler is electrically insulated, the possibility of phase-to-phase faults exists. With this in mind, medium- and high-voltage

couplers should be explosion proof at least to the extent that they remain intact during a phase-to-phase fault. It should also be explosion proof for methane gas if used inby the last open crosscut in gassy mines during a phase-to-phase fault. This would be determined by staging actual phase-to-phase faults on sample designs of a particular coupler.

Phase-to-Phase Fault Protection

The mine trailing-cable electrical system is resistively grounded, which limits a phase-to-ground current to 25 amperes. A phase-to-phase fault, however, may have a current of 3,000 amperes. This means that a phase-to-phase fault may have 5,000 times more energy than a grounded fault. This high-energy fault within a coupler may not cause it to explode and injure those nearby, but it would appear reasonable to minimize its occurrence and limit internal damage to the coupler. The coupler should also be designed and tested to assure that a fault within the coupler is likely to be phase-to-ground, and will not develop into a phase-to-phase fault. A particular coupler design should be tested to break down a number of times under clean and contaminated conditions to establish that phase-to-ground faults are the most likely fault path.

Cable Voltage Discharge

Medium- and high-voltage couplers should be designed such that when the unit is decoupled either the power conductor contacts will be inaccessible to mining personnel, the power conductors will be temporarily shorted to ground one at a time during decoupling inside the explosion proof enclosure, or the cable conductors are shorted to ground at the circuit breaker.

The danger of working on disconnected, but nevertheless charged, high voltage cable has been acknowledged. Mine splice shops have developed practices to reduce the problem, but maintenance and operation by less experienced mine mechanics can result in a severe shock, which could lead to ineffective usage and possible injury.

Conductive Coupler Shell

The coupler shell should be of metallic construction if there is no continuous ground shield surrounding each insulated phase. The metallic portion of the shell must be firmly connected to the ground conductors of the cable and be of sufficient cross section and conductivity to carry the ground currents. Metallic construction should consist of a continuous metal covering starting at the metallic shield termination of the cable and extending over the phase contacts. The continuous metal covering should consist of a solid metal or a woven/braided metal capable of carrying the ground fault currents. The interior of the coupler shell enclosing the contact and termination area should be metallic and bonded to the ground wires. This is a slight departure from current regulation, which require a solid metal shell or enclosure. Electrically, this departure should be adequate. The mechanical aspects of a shell that is not constructed entirely of metal must also be considered.

Nonconductive Shell

If there is a continuous metallic shield surrounding each phase of the coupler, an entirely nonmetallic shell should be permitted. Each metallic shield should also be firmly connected to the ground conductors of the cable.

Each insulated phase of the coupler should be covered with a metallic shield over the entire length from cable shield to cable shield in the two halves of the coupler to provide adequate protection. Shields should be capable of carrying full ground currents.

As long as personnel protection is assured by proper shielding, there is no electrical requirement for a metallic shield on the coupler, although the mechanical aspect must also be considered.

Voltage and Conductor Size Coding

The coupler should be clearly coded, mechanically and visually, to indicate the maximum conductor size and operating voltage. Provisions should also be made for mechanical coding of similar couplers at the power center. Some effort should be devoted do developing easily usable and standardized coding systems. Along with this, reasonable ranges of current and voltage classification must be defined.

Coupler Reliability

The main purpose of these considerations is to encourage coupler designs that are uniformly durable and dependable.

Shell Sealing

There is a need to assure that coupler shell sealing systems are adequate and operable since a trailing-cable coupler is likely to be immersed in water when used in-line and exposed to water and dust on a machine. The mating of the coupler shell halves should be sealed, and the status of the seal monitored by the coupler pilot circuit contact, which closes when the seals have full contact.

Electrical Performance

Trailing-cable couplers should pass a set of electrical performance tests for acceptance as a reliable device. Table 1 contains a list of suggested dielectric test voltages for trailing-cable couplers.

TABLE 1. - Suggested dielectric tests for couplers used in underground mine applications (from IEEE 48-1975)

Insulation class,[1] volts	Max design voltage to ground, volts	1-minute dry withstand, kv	6-hour dry withstand, kv	Partial discharge (corona) extinction test		Lightning impulse 1.2/50, kv	Direct voltage test 15-minute dry withstand, kv
				Extinction voltage Rm kv	Min. detector sensitivity, pC		
661-1,000	635	15	7.5	0.9	3	50	35
2,500	1,600	20	10	2	3	60	40
5,000	3,200	25	15	4.5	3	75	50
8,700	5,500	35	25	7.5	3	95	65

[1]Value of various test voltages are the same as used in IEEE standard 48-1975 for cable termination except for the 661- to 1,000-volt insulation class. These values were extrapolated down from the higher voltage class test values.

For the purposes of these dielectric tests, the insulation is expected to remain dry during normal operation. It was reported that even small amounts of water will cause insulation failure. Therefore, we have concluded at this time that no coupler can operate with wet insulation, and that some means must be devised to keep it dry. The dielectric tests are primarily intended for insulation systems that utilize exposed surfaces as creepage paths to ground. Other types of insulation systems such as premolded or preformed splice configurations, which have no exposed surfaces, are not considered. ANSI test standards for premolded splices, the category into which trailing cable connectors could fall, have not been used in order to insure that the coupler shall perform satisfactorily until the standards are produced.

Electrical Proof Tests

Nondestructive electrical proof tests should be conducted on all installed and repaired couplers. These suggested direct-current test voltages should be the same as test voltages for the cable itself. For the present, a 12-kv-dc withstand for 5 minutes is suggested. In the future, the voltage levels described in table 2 should be considered for both the repaired cable and installed coupler.

TABLE 2. - Test voltages (kv) for installed couplers and cable (75 percent of new cable test voltages)

Conductor size.....	AWG 8	AWG 6-AWG 2	AWG 1-AWG 4/0	250-550 C.M.	550-1,000 C.M.
Cross-linked polyethylene or EPR-insulated:					
Unshielded:					
0-2,000 volts...	15.8	15.8	18.0	21.4	25.9
2,001-5,000 volts...	26.3	26.3	26.3	-	-
Shielded: 5,000-8,000 volts.....	-	33.8	33.8	33.8	-
Rubber-insulated:					
Without O-R:					
0- 600 volts...	7.9	7.9	9.0	11.3	13.5
601-1,000 volts...	11.3	13.5	16.9	20.3	22.5
1,000-2,000 volts...	13.5	16.9	20.3	22.5	-
With O-R:					
0- 600 volts...	13.5	13.5	16.9	19.1	22.5
601-1,000 volts...	13.5	16.9	19.1	22.5	25.9
1,001-2,000 volts...	16.9	19.1	22.5	25.9	-
2,001-3,000 volts...	22.5	25.9	25.9	26.3	-
3,001-5,000 volts...	-	26.3	26.3	26.3	-
5,001-8,000 volts...	-	33.8	33.8	33.8	-

NOTE--O-R = ozone-resisting insulation; C.M. = circular mils.

Mechanical Performance Test

The coupler should pass a set of mechanical performance tests before it is accepted as a reliable device. The primary purpose of the mechanical performance tests is to assure the reliable operation of the coupler shell. The shell must protect the internal electrical components of the coupler during operation in the severe mine environment. The mechanical performance test should include the following:

1. Cyclic tensioning should be done under simulated operating configurations with cable installed. For cyclic-tension testing, the parameters should be determined from actual field data. The tests should prove that the strain relief method used in the coupler is sufficient for mine conditions.

2. Crush-resistance testing should be based on the highest likely machine runover or roof-fall loads.

3. Abrasion-resistance testing should be based on the average distance an in-line might be dragged in normal use.

4. Engagement cyclic operation should be tested based on the likely number of times a coupler would be engaged and disengaged.

5. Shock and vibration resistances should be tested under accelerated conditions that a coupler would experience on a mining or other types of machines. The parameters for these tests should be determined from actual measurements of the vibration forces.

6. Resistance to mine water ingress should be tested by immersion to simulate wet mine conditions.

7. All mechanical performance tests should also meet the requirements of NEMA standard No. PR 1-1975. Electrical performance tests should be conducted after the mechanical tests.

Protective Covers

The reliable operation of cable couplers, especially at high voltage, depends primarily on keeping water and dust from collecting on the coupler insulation surfaces when the coupler halves are separated. The trailing-cable coupler should have an interlocking, automatically actuated, or pilot-circuit monitored protective covers to retard the entry of water and prevent the entry of dust while the coupler is decoupled.

Coupler Insulation Cleaning

Coupler insulation materials should be compatable with cleaning solvents. If the coupler insulators become contaminated, the use of a solvent may facilitate cleaning. Appropriate standard tests should be conducted to show that a particular solvent does not cause deterioration and swelling of the insulating materials nor deteriorate the insulation electrical performance of the insulation.

Outdoor Storage

The coupler shell and protective cover should be constructed to withstand outdoor storage. The coupler with its cover in place should be subjected to a static pressure test of 30 psi to establish that it seals properly.

Coupler Human Engineering

The purpose of these considerations is to encourage coupler designs that are used easily in a poor operating environment.

Weight

Each half of the coupler should be designed so that (1) it is not too large and bulky to be handled by one person, and (2) its weight, not including cable and cover but including the filler, does not exceed 45 pounds.

Engagement Forces

The coupler should be designed to allow ease of alinement, engagement, and disengagement. Furthermore, the force required to rotate the mechanism should not be in excess of 50 pounds unless a tool is used. The force required to pull apart the unlatched mechanism should not be in excess of 85 pounds, and the force to push together the mechanism for latching should not be in excess of 55 pounds.

Surface Temperature

When the coupler is operating and accessible to operating personnel, its surface temperature should not exceed 70° C.

Exposed Conducting Surfaces

If an entirely metallic shell is used on a coupler, all exposed conducting and metal parts shall be covered with electrical insulating material. It has been reported that the miners generally have an aversion to touching exposed metal surfaces on a coupler. Many coupler manufacturers already provide such coverings.

RECOMMENDATIONS

At this time, the use of trailing cable couplers is limited due to the inconvenience of present couplers and the attractiveness of underground splice kits over the present couplers. To make the coupler attractive, it is recommended that specific requirements, formulated from these considerations, be established as guidelines and regulations that will assure that the coupler performs without being a nuisance in the trailing-cable system, especially for the in-line applications.

To make the ever-popular splices on trailing cables safer and more durable, it is recommended that specific requirements, formulated from these

considerations, be established as guidelines and regulations that will improve the present performance of splices on trailing cables.

Finally, although our work has identified many problems and presented solutions for some, it is but a part of an effort to solve the major problems with medium- and high-voltage trailing-cable splice and coupler connections.

DEVELOPMENT OF CRIMP CONNECTOR AND SPLICE-INSULATING KIT FOR TRAILING CABLES

by

Walter J. Frank, Jr.[1]

ABSTRACT

This report summarizes work done under Bureau of Mines contract H0357100, "Development of a Crimp Connector for Trailing Cable Splices." The purpose of this effort was to establish optimum connector design conditions to meet flex cycle, pullout and electrical resistance criteria on phase power conductors. Field testing of "optimum design" connectors is briefly discussed.

One of the primary objectives of contract H0357100 was to enable one to design better performing phase conductor connectors. Illustrating the practical significance of this is a discussion on the development of a new splice kit for trailing cables. The connectors in this kit were designed in accordance with the design methods described in the contract final report. Kit components, test data, and a connector installation tool are also discussed.

The successful effort on the phase connector has resulted in contract H0377042, entitled "Design and Testing of Joining Sleeves for Trailing Cable Ground and Pilot Wires." The purpose of this contract (currently in effect) is to improve ground-conductor and pilot-wire performance. Significant findings to date are discussed.

INTRODUCTION

Present underground coal mining machines receive their power via portable cables known as "trailing cables," which connect vehicles such as shuttle cars to the electrical load centers. Use of this equipment results in a constant paying out and rewinding of the cable by means of spooling and sheave devices. This results in a continuous flexing, pulling, and abrading of the cable. In addition, poor lighting, restricted space, and other mobile equipment constantly running over the cables result in an aggregate of operational and environmental conditions that cause frequent cable damage.

Damaged cable must be either replaced or repaired by splicing. Splicing involves less downtime than when replacing the entire cable. However, this economic advantage may be significantly reduced because subsequent failures usually occur more frequently at the previously spliced joints.

Improvement in the splice connection would increase splice longevity, decrease downtime, and enhance mine safety. This report is the result of such an effort. It ties together work completed to improve the performance

[1]Mechanical engineer, Burndy Corp., Norwalk, Conn.

of the phase power conductor connector and work presently in progress on ground conductor and pilot wires. The practical significance of this work is reflected in a discussion of a superior performing splice kit development.

PHASE POWER CONNECTOR DEVELOPMENT

This work was carried out under Bureau of Mines contract H0357100. It includes the development of a test procedure, a glossary of pertinent connector design terminology, definition of various conductor joints, connector design parameter study, a connector design guide, and a field performance study.

Development of a test procedure was necessary in order to evaluate existing splice methods as well as new ones. It resulted in adopting the tests for flex, pullout, relative resistance, and heat run.

The flex test examines the ability of splices to withstand the bending effects induced by shuttle car sheave wheels. A machine was constructed to simulate these effects (fig. 1). Figure 2 shows the bending sequence.

The pullout test determines the holding strength of the connector. It assures the holding power of conductors under the severe cable loading conditions found in a mine.

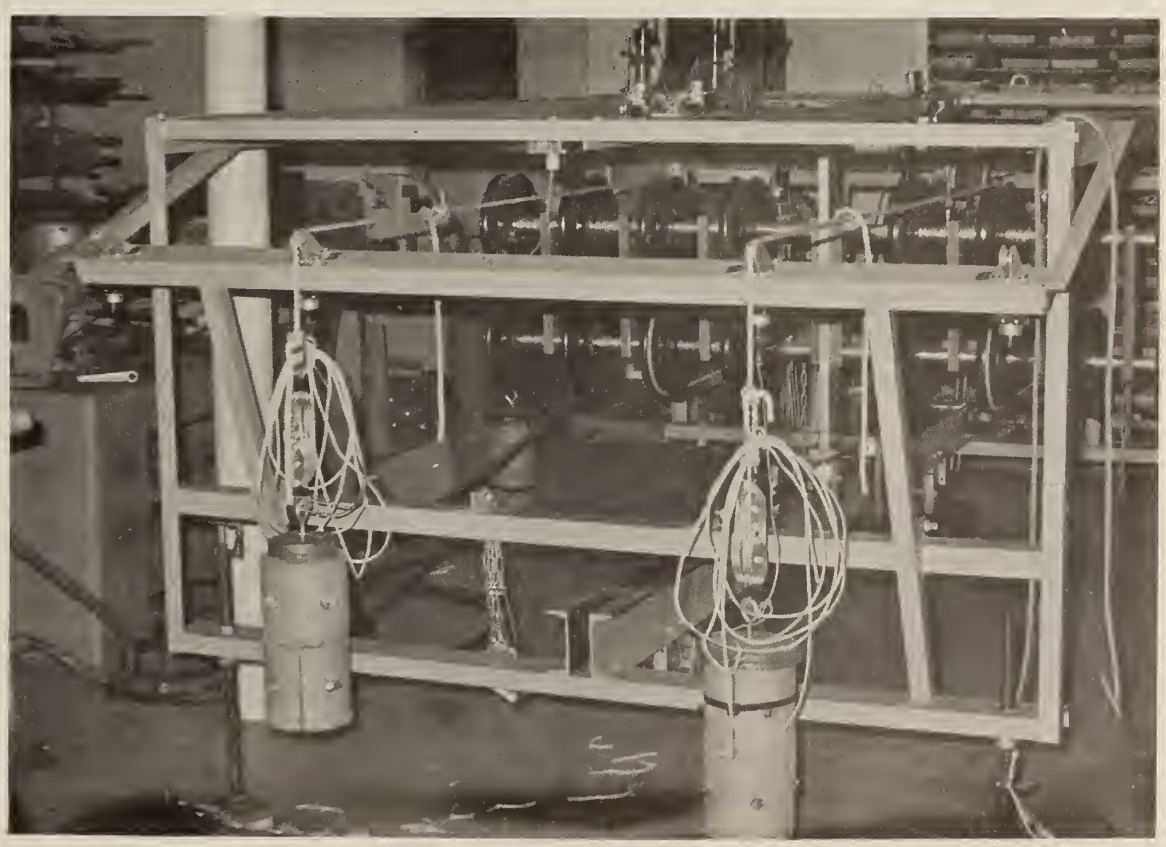
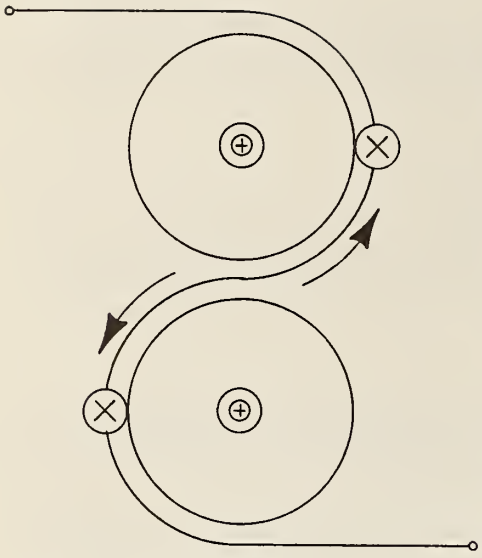


FIGURE 1. - Flex machine.



X = Connector Stop Location

FIGURE 2. - Flex bending sequence.

Relative resistance and heat run are electrical tests to insure that the resulting connection is electrically equal to or better than an unconnected conductor.

Test criteria were selected from previous Bureau work as well as from established connector design practice. A typical example for a no. 4 size conductor is as follows:

Flex cycle life	- 1,500 cycles minimum.
Conductor pullout	- 650 pounds minimum.
Relative resistance	- 100 percent, maximum.
Heat run	- Must run cooler than an equivalent conductor when subjected to current overloads.

Conductor joint types are defined and include lap, butt, crowsfoot, and modified crowsfoot (figs. 3-6).

A study of joint type performances resulted in the selection of the modified crowsfoot joint for the following reasons:

1. One crimp completes the joint.

2. Easy longitudinal alinement of cable conductor for tensile load equalization.

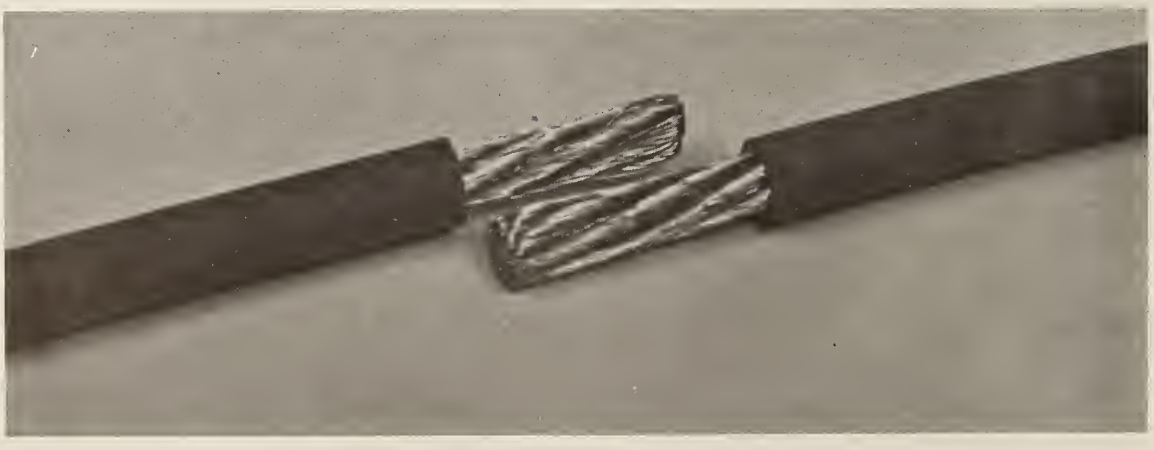


FIGURE 3. - Lap joint.

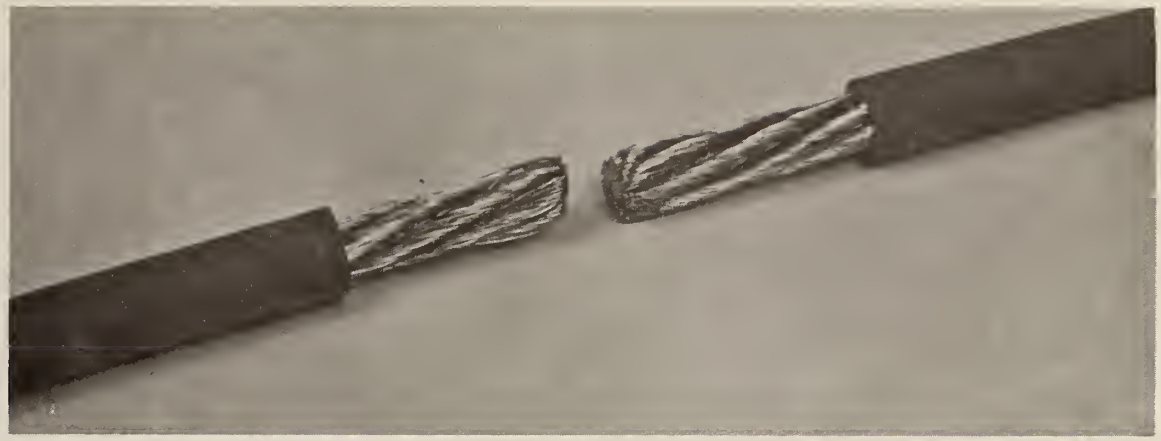


FIGURE 4. - Butt joint.

FIGURE 5. - Crowsfoot joint.

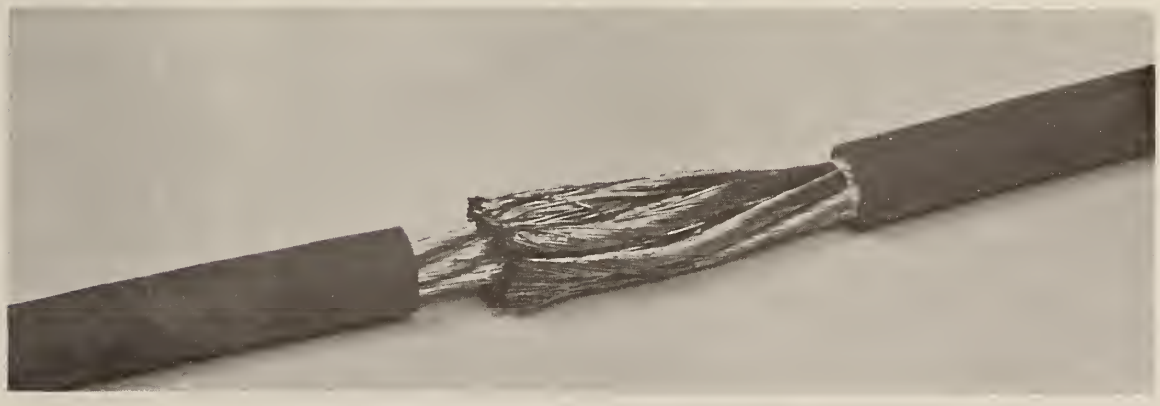


FIGURE 6. - Modified crowsfoot joint.

3. High pullout strengths.

4. "In-line" connection of conductors (minimize overall splice size).

The study of connector design resulted in optimizing the following areas affecting connector performance:

Connector cross section

Crimping force

Connector metallurgy

Joint type

Conductor overlap

Insulation strip distance from connector

Crimp contact length

Percent compression

Crimp profile

Crimp stress relief

Flare angle

Shroud

Figure 7 shows the resulting optimum design connector for no. 4 and no. 2 conductors. Figure 8 shows crimp die shape, which incorporates crimp contact length, percent compression, and crimp stress relief design features.

FIGURE 7. - No. 4 STR and No. 2 STR test connectors.

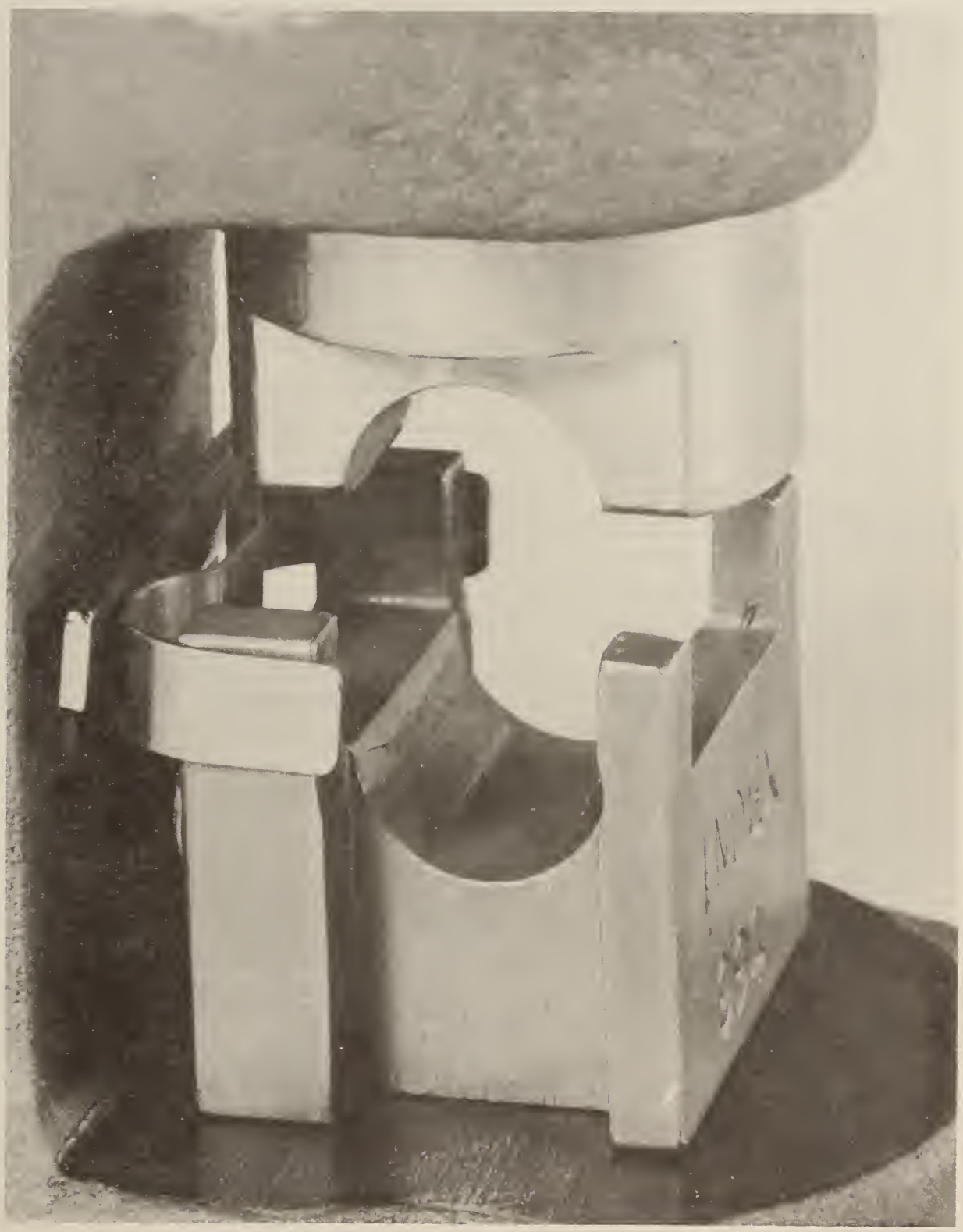


FIGURE 8. - Crimping die.

Table 1 compares the improved performance of the developed connector with that of commercially available connectors and the square knot. Relative resistance levels of the developed connector were 100 percent or less, and test jumpers incorporating the connector ran cooler than unconnected jumpers with overload currents.

TABLE 1. - Modified crowsfoot connector performance summary

Size No.	Connector developed per contract		Commercially available connectors		Square knot	
	Number of flex cycles (average)	Pullout (average), lb	Number of flex cycles (typical)	Pullout (typical), lb	Number of flex cycles (typical)	Pullout (average), lb (typical)
4	3,642	1,070	968	562	798	719
2	1,953	1,313	1,286	1,362	464	1,065

Table 2 shows how the probable design features affect each other in relation to connector performance.

A suggested design procedure enables the design of connectors for the power phase conductors that will optimize performance when tested as previously discussed.

During the course of this development study, cursory examinations uncovered other factors that also effect splice performance. These include installation techniques, selection of insulation components, and performance differences between cable manufacturers. In-depth studies on these parameters should be considered to complete the total splice picture.

TABLE 2. - Design parameter effects

Constant parameters	Varying parameters: Connector cross section	Crimping force	Connector metallurgy	Joint type	Conductor overlap	Insulation strip distance from connector	Crimp contact length	Percent compression	Crimp profile	Crimp stress relief	Flare angle	Shroud
Connector cross section	X	N	P	P	N	N	N	P	P	N	N	N
Crimping force	P	X	P	P	N	N	P	P	P	P	N	N
Connector metallurgy	P	P	X	N	N	N	P	P	P	P	P	P
Joint type	P	P	P	X	P	P	P	P	P	P	P	N
Conductor overlap	N	N	N	P	X	P	P	N	N	N	N	N
Insulation strip distance from connector	N	N	N	P	N	X	N	N	N	N	N	P
Crimp contact length	P	P	P	P	P	N	X	P	P	P	N	N
Percent compression	P	P	P	P	N	N	P	X	P	N	N	N
Crimp profile (geometry)	N	P	P	P	N	N	P	P	X	N	N	N
Crimp stress relief	P	P	P	P	N	N	N	P	P	X	N	N
Flare angle	N	N	P	P	N	N	N	N	N	P	N	Note 3
Shroud	N	N	P	P	N	P	N	N	N	N	Note 3	X

NOTES--1. P means constant parameter will probably be affected by a change in varying parameter.
2. N means constant parameter will probably not be affected by a change in varying parameter.
3. Does not apply.
4. A change is defined as affecting flex life, pullout, electrical resistance or combination thereof.
5. Fixed dimension crimp tooling assumed (not pressure sensitive).
6. Crimp profile refers to different plane geometrical shapes (not similar shapes).

FIGURE 9. - Beat block installation tool.

SPLICE KIT DEVELOPMENT

In order to illustrate the practical significance of the phase power connector development, the development of a commercial splice kit will be briefly discussed.

Following the connector design suggestions developed under contract H0357100, connectors were designed for No. 4 and No. 2 type W and type G twin-conductor shuttle car trailing cable. These connectors are similar to those shown in figure 7 and contain the optimum design features developed under the contract; they are for use on the modified crowsfoot joint (fig. 6).

A "beat block" installation tool was developed to facilitate a simple, accurate installation method (fig. 9). Salient features include the following:

1. Optimum crimp profile, crimp contact length, and crimp stress-relief angles.

2. Butting crimping dies, which guarantee the same crimped cross section from one installation to the next.

3. A visual indicator to show the installer when crimping die butts and installation is complete.

4. Physical dimensions that minimize conductor disturbance and thus help to position connection in a manner to equalize conductor tensile loading when in use.

As with the connector, development of the installation tool was a direct result of contract H0357100.

The balance of the splice kit includes the following:

1. Ground connector for type G cable.

2. Inner heat-shrink sleeves with hot-melt adhesive for insulating phase and ground connections.

3. Outer heat-shrink sleeve with hot-melt adhesive (includes heat indicating paint to insure proper shrink).

4. Abrasive cloth for cleaning and roughing cable jacket to insure shrink sleeve adhesive bond.

5. Instruction sheet.

6. Cable-cutting and insulation-stripping template. Figure 10 shows the complete splice kit.

Mine Cable Splice Kit
For #
2 Conductor Flat Cable Type W or G
P-169-2-MESA
Use Burndy HYTOOL® BBM4 or die set U994
Cat. No. CMS4KIT
BURNDY
BURNDY #4 2 Conductor Flat Cable Type W or G

FIGURE 10. - Splice kit.

As previously mentioned, our work under the contract included cursory examinations on the effects of insulation and installation technique on splice life. An outgrowth of this work has been the selection of kit insulating components that are compatible with the optimum design connectors. The required installation technique is such that tensile load equalization of the cable conductors will be assured.

Table 3 shows the superior performance of this kit; an advantage any manufacturer can obtain by utilizing the results of work conducted under contract H0357100.

TABLE 3. - Performance comparison of selected splice kits

Kit description	Flex cycles		Pullout, pounds	
	No. 4 cable type W	No. 2 cable type W	No. 4 cable type W	No. 2 cable type W
Kit developed per contract.	3,309	4,750	2,235	2,625
Kit A (commercially available.....	497	952	1,615	1,775
Kit B (commercially available)--butt splice connector recommended.....	226	408	1,245	1,755
Kit C (commercially available)--used with beat-ring connector.....	262	1,266	469	1,062

FIELD TESTING

Under contract H0357100, a field test program was instituted in order to determine the suitability of the developed connector and associated installation tooling in a mine environment.

Over 100 connector installations were made on No. 2 and No. 4 flat, twin trailing cables. The results showed that the connectors and installation tooling were suitable for the intended application. Test details are included in the contract final report.[2]

At the time of this writing, we are engaged in a long-term field-test program on the splice kit. Initial results concerning splice longevity are encouraging.

[2]Frank, W. J., Jr. Development of a Crimp Connector for Trailing Cable Splices. BuMines Open File Rept. 58-77, 1976, 89 pp.; available for reference at Bureau of Mines facilities in Denver, Colo., Twin Cities, Minn., Bruceton and Pittsburgh, Pa., and Spokane, Wash.; U.S. Department of Energy's Carbondale Research Operations, Carbondale, Ill., and Morgantown Energy Research Center, Morgantown, W. Va.; and National Library of Natural Resources, U.S. Department of the Interior, Washington, D.C.; and from National Technical Information Service, Springfield, Va., PB 266 027/AS.

DEVELOPMENT OF GROUND CONDUCTORS AND PILOT-WIRE CONNECTORS

Bureau contract H0377042 has authorized work on improving ground conductor and pilot wire splices. This work was suggested as the result of information gained in performing the previously described work, but does not directly affect the results of that research. At the time of this writing, the contract is still in effect and mine tests are in progress. This section of the report will summarize significant work to date.

The development effort comprises the following categories:

1. Present-practice investigation.

2. Test procedure development.

3. Cable performance study.

4. Connector design study.

5. Field test.

6. Final report.

PRESENT-PRACTICE INVESTIGATION

The present-practice investigation is complete. Its purpose was to determine methods currently used to connect the ground and pilot wires, which include overlapping conductors and taping (illegal but frequently used), twisting or roping conductors together, square knots (illegal), and use of presently available connectors for phase conductors.

From this investigation, it was determined that the contract should result in a ground connection that is superior to the phase connections. Although ground monitoring systems are required by law, a ground connector that outperforms the phase connection will minimize the seriousness of a premature pilot-wire failure.

Type of trailing cables considered include two-conductor, flat, type G; three-conductor, flat, type G-GC; three-conductor, round, type G-GC.

TEST-PROCEDURE DEVELOPMENT

Test-procedure development, which has been completed, and has resulted in the following tests for evaluating ground conductors: tension test, short-circuit test, and flex test.

The tension test determines connector holding strength and controls the amount of force applied to the conductors, which is necessary to insure acceptable short-circuit performance. At the present time, we are thinking in terms of a 15-pound minimum to 50-pound maximum pullout. (See tables 1-2 for comparison data.)

The short-circuit test investigates the ability of the connector to carry high currents for a short period of time as may be experienced in a phase-to-phase fault in a solidly grounded system. Test amperage and times are based on the formula

$$\left[\frac{1}{A}\right]^2 t = 0.0297 \text{ LOG } \left[\frac{T_2 + 234}{T_1 + 234}\right].$$

Tests are run at 1 cycle (0.0167 second) and 100 cycles (1.667 seconds), with current levels based on conductor size. This relationship was extracted from the Insulated Power Cable Engineers Association data (IPCEA).[3]

Criteria for acceptable connector performance are that the connector must physically hold together, show no evidence of physical change, and maintain system continuity.

Cable flex testing similar to that done in the phase connector development will be done to verify the superior performance of the ground connectors compared with that of the phase connectors.

The test procedure for the pilot-wire connector will follow that of the ground connector with the exception of the short-circuit test which is not applicable to the pilot wire circuit.

CABLE-PERFORMANCE STUDY

The cable-performance study is now complete. This work included study of the interaction of cable conductors with respect to one another. Both flat and round cables were studied. The most significant finding is the necessity of the ground connection to slip so that cable tension loading of the ground or pilot wires, a significant improvement in flex life of these connections, is obtained. This coupled with good connector design should result in superior longevity over that of the phase connections.

Another significant finding relates to employing a proper installation technique when splicing round G-GC conductors. Proper insulation of all connections is required to eliminate premature failure caused by abrasion of a connection on adjacent conductors. This and penciling (tapering) of conductor and jacket insulation was found necessary to insure superior ground- and pilot-wire performance. Figure 11 shows cable after flex testing. (Note phase failure while ground and pilot wires are still connected.)

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[3]Insulated Power Cable Engineers Association. Guide for Application of Maximum Insulation Temperatures at the Conductor for Rubber-, Thermoplastic-, Varnished-, Cloth-, and Asbestos-Insulated Cables. Ch. in Power Cable Ampacities. P-46-426, 1962, pp. XVI-XVIII.

FIGURE 11. - Flex test--round cable type G-GC.

CONDUCTOR DESIGN PARAMETER STUDY

The connector design study is presently in progress. The purpose of this study is to develop optimum performing connector designs for ground and pilot wires. A spring-clip (fig. 12) and a crimp (fig. 13) connector are being investigated. Connector designs will be developed for both flat and round trailing cables. This work should culminate in connectors that meet tensile-slip, short-circuit, and flex criteria, and provide design criteria to enable the design of ground connections that outlast the phase connections.

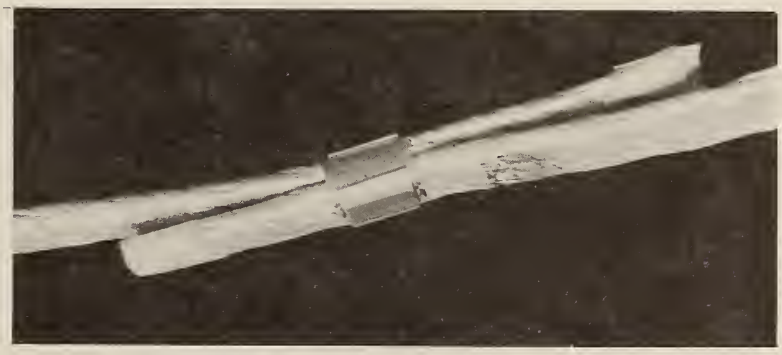

FIGURE 12. - Spring connector design.

FIGURE 13. - Crimp-type ground connector.

After completion of the design study, a field-test program will be conducted to validate connectors and installation procedures in a mine environment.

SUMMARY AND CONCLUSIONS

This report has described completed research on design of a phase conductor joining sleeve and work in progress on joining sleeves for ground and pilot wires. The phase wire sleeve selected for development is suitable for making a "modified crowsfoot" splice joint, and can be relied upon to give typical pullout strengths of 1,000 pounds per conductor and typical flex life of 3,000 cycles in tests of single AWG No. 4 conductors and 1,800 cycles in AWG No. 2 conductors. A modification of this sleeve design was later incorporated by Burndy Corp. into a splice kit intended for the mining market; it has also been under consideration by other splice kit suppliers.

The designs for the ground and pilot wire connectors incorporate the ability to slip a little while the splice is being made, to insure that the phase wires, which are larger and, therefore, mechanically stronger, bear any tensile load. The ground- and pilot-wire sleeves must, however, maintain low contact resistance throughout the life of the splice, including times when ground-fault current surges. The research on these joining sleeves is still in progress.

RECENT DEVELOPMENTS IN LOCATING CABLE FAULTS

by

George J. Conroy[1]

ABSTRACT

Techniques for locating trailing-cable faults are discussed, particularly those techniques suitable for use in underground coal mines, which have been the subjects of Bureau of Mines research. The discussion concerns precautions and suggestions for locating faults, rather than detailed descriptions of apparatus.

INTRODUCTION

Methods of locating faults in trailing cables are not universally successful, but they can reduce the total time devoted to troubleshooting. Their prime area of application is in finding very low-resistance short circuits, and they also have demonstrated utility in locating open circuits. Success often depends on how the methods are used and what the operator expects of them. If the operator realizes that sometimes a mere clue is useful, and does not insist on always receiving unequivocal indications of fault location, the operator may be reasonably satisfied with the equipment. Otherwise, he or she may cast it aside as useless.

This paper presents cable-fault locating techniques other than time domain reflectometry. It is almost axiomatic that no one fault-locating technique can be depended upon to locate all of the faults occurring in mining cables because the very definition of what constitutes a fault changes with application. For example, megohmeter measurements of the trailing cables in everyday use in several coal mines have in several cases provided values well below 1 megohm and as low as 10,000 ohms, yet the cables continued to be used. In one instance, while measuring ground conductor currents in several 480-volt cables, it was observed that leakage currents averaged about 0.1 ampere, which can be translated to mean that shunt resistance between phase conductors and ground wire at each splice was about 2,700 ohms. You may have your own opinions as to whether these should be considered faulted cables, but the fact remains that in the applications studied, they were not so considered. At the same time, in one mine visited during fault location experiments, longwall cables were replaced if they had less than 1 megohm insulation resistance because they would trip the ground-fault relays due to the very sensitive settings employed at that mine.

An important point is that, in the last situation, a particular fault-locating instrument that could reliably and easily locate short circuits with

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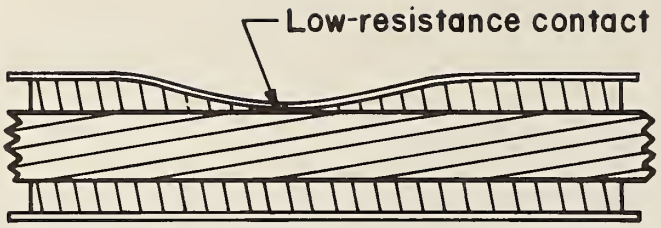
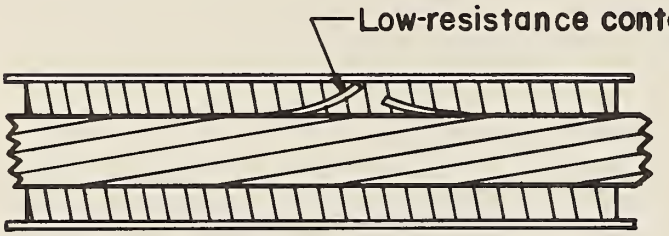
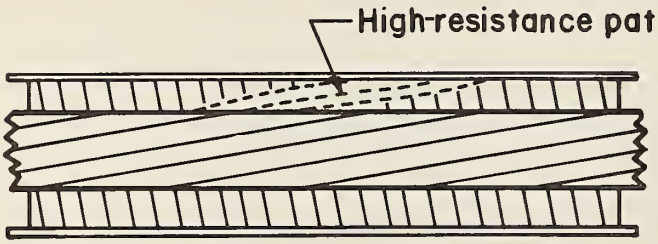


A. Crushed insulation, shield in contact with wire.



B. Broken strand in contact with shield.



C. Carbon track through insulation.

FIGURE 1. - Examples of shunt faults.

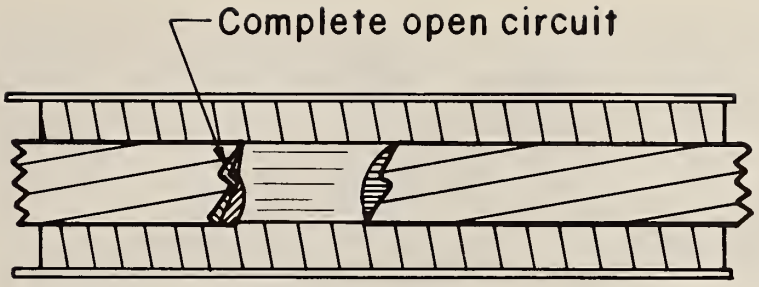
only a few ohms of resistance could not provide even an indication of bad cable. Available equipment that would have worked here was too unwieldly, too expensive, and operated at a voltage too high to be suitable for locating common faults in trailing cables in the face area of an underground mine. Also, even though it does indicate a problem, such equipment might nevertheless give an equivocal reading of fault location, and probably would require considerable skill in interpretation or much repetitive testing, or both. If the voltage is very high, there sometimes might be a question as to whether the test has detected or generated the fault.

Some arbitrary definitions applicable to faults are desirable in order to place some boundaries on the research problem. These boundaries and definitions may be modified as the sensitivities and capabilities of available items of equipment expand. The present capability leads to the following:

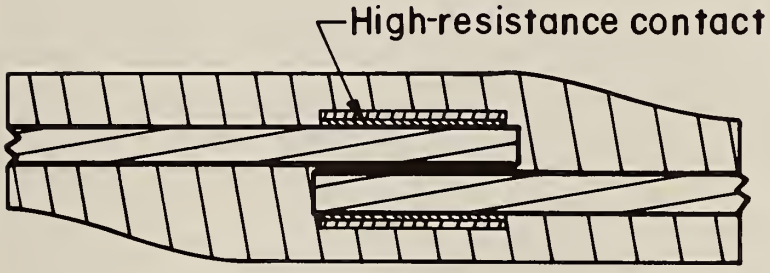
A shunt fault (fig. 1) may be considered as any anomaly observable between two conductors or between a conductor and ground with less than 1,000 ohms of resistance.

A series fault (fig. 2) may be considered as any anomaly that results in a rise in conductor resistance greater than 100 ohms.

There is a particular situation where the second definition is in trouble immediately; that is, in splices. A normally satisfactory splice in a trailing cable would have only a few milliohms series resistance; and any indication of higher resistance may be considered a sign that the splice will soon cause trouble; in this case a very low resistance might be considered a series fault. In some cases, this type of anomaly might be fairly easily detected by



A. Broken, separated wire.



B. Poor contact at splice joint.

FIGURE 2. - Examples of series faults.

infrared thermometer readings, especially if they are taken while the cable is transferring the normal current of several hundred amperes to a machine. Subject to some factors of judgement, an experienced person might even be able to tell by local temperature that a given cable splice is poorer than others. However, I choose to regard these indications as examples of splice quality recognition, rather than cable fault location. The "location" aspect is secondary in this case; we already know the location of the splice, and we are now interested in detecting deviations from normal. Some of our techniques of detection might work well here, yet be completely impractical in finding a fault that has left no telltale signs on the sheath of the cable. Measurements may be assisted by twisting and flexing the cable at the splice; however, this could not be done conveniently for every foot of the cable.

The first step in locating a fault, beyond that of removing the cable from the source of power, should be to measure its resistance. Often, the first measurement is with a megohmmeter. A typical instrument is shown in figure 3. The various high-voltage ranges of the instrument can be used to detect the presence of shunt faults, including damage to outer insulation; the "ohms" scale can be used to check conductor continuity to find completely open circuits. It is also advisable to use a multimeter to take similar readings. The megohmmeter tends to read lower than the multimeter for many types of cable fault because of the higher voltage used. The problem is that just a few extra ohms of resistance can indicate that certain fault location methods are unsuitable for the particular problem. There may also be a difference in the response between a modern, high-input-impedance, digital meter and an ordinary meter utilizing a D'Arsonval movement. Also, some of the available fault-locating devices will give an indication specifically saying "short" or "open"; and these indications may be thought of as taking the place of the ohmmeter measurement. However, present experience indicates that, for many of the low-resistance measurements concerned, more confidence can be placed in simple circuits such as those used in common multimeters with D'Arsonval movements than in complex electronic circuits that may have some internal

FIGURE 3. - Megohmmeter.

adjustments, drift, etc., that could influence the indication. When the TDR or other fault locator indicates that there is a problem at a location a certain number of feet down the cable, the repairman wants to know that there really is a short circuit instead of wondering whether what the instrument sees is a short circuit, just a change in insulation characteristics, or some vaguery of the meter circuit.

Having definitely established the character of the fault, the worker would ordinarily attempt to find its approximate location by operating some piece of hardware at the terminal end of the cable and obtaining a distance reading. This might be the microprocessor TDR described in another paper presented here, or a simpler TDR, or a different device. In underground work, it probably will not be a thumper or other high-voltage, high-energy device, even if a means of obtaining a distance reading at the cable terminals is made possible, since the uncontrolled nature of the area in which these trailing cables lie could contribute a personnel shock hazard or the danger of igniting combustibles. Pulses of very short duration at reasonably high voltages might be acceptable if so proven by ignition and other tests; however, to date, most of the Bureau's research effort has been concentrated in the range below 45 volts. This has been true because of the difficulty of switching higher voltages at nonosecond speeds, as required for a TDR. Incidentally, there may be higher voltages present interior to the fault-locating apparatus if a cathode ray tube is used; in this event, it is not safe to have the actual instrument beyond the last open crosscut. This restriction is usually not a major concern for most cables since the terminals to which the connections are made will normally be at the load center, which is in the fresh air. Any electrical probes, however, used to traverse the cable must be established as being intrinsically safe.

Although the TDR may provide an indication that is nominally in feet, it must be calibrated with respect to the cable being examined before an actual electrical footage reading can be obtained. In many cases, it might be possible to exercise foresight and measure cables accurately, keeping a record of their total length. Often there will be at least one pair of conductors that is not severely faulted, so that pulse energy can reach the far end of the cable; there it would be reflected and thus provide a "mark" to calibrate the TDR. It may be difficult to measure the electrical length of the cable at the time of the attempt to locate the fault, due to loops, interlaying with other cables, etc. If for such reasons only an approximate location is obtained with the TDR, it would be convenient to have a probe method of precisely locating the fault by traversing the cable. Even where the electrical footage reading can be depended on to be accurate, there is an advantage to the probe. Its indication is direct with regard to the external situation, and not subject to errors in pacing off or measuring a physical distance along the cable that corresponds to the electrical reading.

Probe techniques may involve acoustic or electrical sensing of high-voltage breakdown (though probably not in underground fault locations); detection of a temperature rise due to a local shunt fault by utilizing an infrared thermometer and probably a high-current, low-voltage supply; sensing of electromagnetic fields by induction; or sensing an electrostatic field. The latter two methods have been embodied in a single probe during Bureau research as shown in figure 4. The infrared measurements may be made with

FIGURE 4. - Electromagnetic-electrostatic field sensing probe.

the Bureau probe shown in figure 5, or might be made with a commercial unit such as that shown in figure 6. None of these probes is completely satisfactory for all applications. The infrared unit works only on shunt faults with resistance lower than 60 ohms except for the splice-quality inspection mentioned earlier. Otherwise, the watt density developed is insufficient to raise the local cable temperature to the 1° or 2° F necessary for detection.

FIGURE 5. - Infrared fault-locating probe.

FIGURE 6. - Commercially available infrared thermometer.

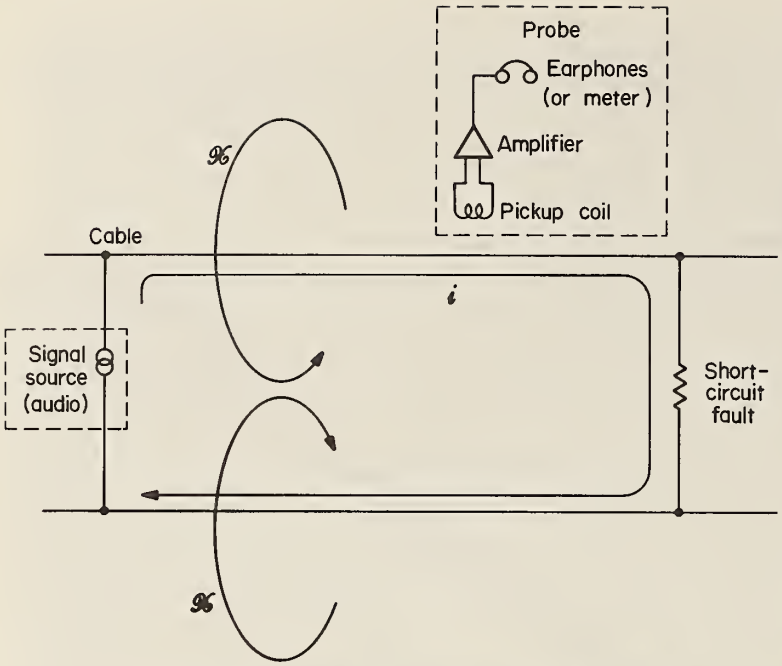


FIGURE 7. - Electromagnetic tone tracer.

One advantage of the infrared system is that it can work with shielded cable, at least to some extent. It has been known to fail in finding a fault on a pilot wire embedded exactly at the center or a G+GC cable, and there are other frustrating aspects of its use, but nevertheless it has attractive qualities.

The electromagnetic probe works for shunt faults also, but is even more restricted than the infrared system, reacting only to faults with resistance of less than about 4 ohms, at least in the case of the straightforward circuit in the probe illustrated in figure 7. In this probe, as the alternating current passes through the shunt fault, a meter deflection or a drop in tone amplitude is noted, marking the location. Fault current, and therefore the induced current, is diminished with increased resistance; the sensing amplifier begins to respond also to the electrostatic field caused by the applied voltage on the faulted conductor. Because this voltage is present in the region past the shunt fault, the expected sudden dip in indicated signal strength fails to occur as the probe passes a high resistance shunt fault. Thus, the probe fails in its purpose.

The electrostatic-field-sensing function of the probe is successful only for series faults whose impedance is higher than about 400 ohms, since otherwise the voltage will not be shunted out by the natural, characteristic impedance of the cable; instead, it will appear throughout the entire length beyond the fault, giving an effect analogous to that encountered with the electromagnetic field.

The electromagnetic-field-sensing principle is not usually considered applicable to series faults; however, in our experiments with the high-voltage (up to 300 volts) tone generator and cable-route tracer (fig. 8), it was noted that this combination could provide clues as to the presence of an open circuit as well as that of a shunt fault. This led to the recommendation to several interested persons that the system be tested in their own mines for both types of faults. Unfortunately, no feedback has been received regarding the success of the tests.

A miniature version of the electromagnetic-electrostatic sensing system was developed in our laboratory and found to function for shunt and series faults, and even provide clues to faults in some shielded cables. The set

FIGURE 8. - Tone generator and cable-route tracer used as cable-fault locator.

shown in figure 9 was packaged by Bendix under current Bureau contract H0366020 entitled "Microprocessor TDR." Field test models of the unit are now being tested in the laboratory with some success on flat cables; some questions remain with regard to round cables.

The swept frequency system can function either as a terminal-connected device like the TDR, or a terminal device and traversing probe system like the audio electromagnetic-electrostatic field sensing scheme, or as a probe with no source of signal at the cable terminals. The method is being developed by Stanford Research Institute under Bureau contract H0166082, "Cable Fault Locator Research." The present version of this apparatus is shown in figure 10.

For the terminal-connected mode of operation, connection is made to the faulted cable pair at the terminals, and the characteristic impedance of the pair is sounded by a signal whose frequency is swept from 10 to 45 megahertz at a sweep rate of 100 megahertz per second. A directional coupler senses the reflected signal, the various frequency components of which have amplitudes determined by the distance along the conductor from terminal to fault as it relates to the wavelength associated with each frequency. The reflected signal is mixed to produce lower frequency tones in which the tone frequency is given by the equation

$$ft = tS,$$

where t is the round trip time to a reflecting discontinuity and S is the sweep rate.

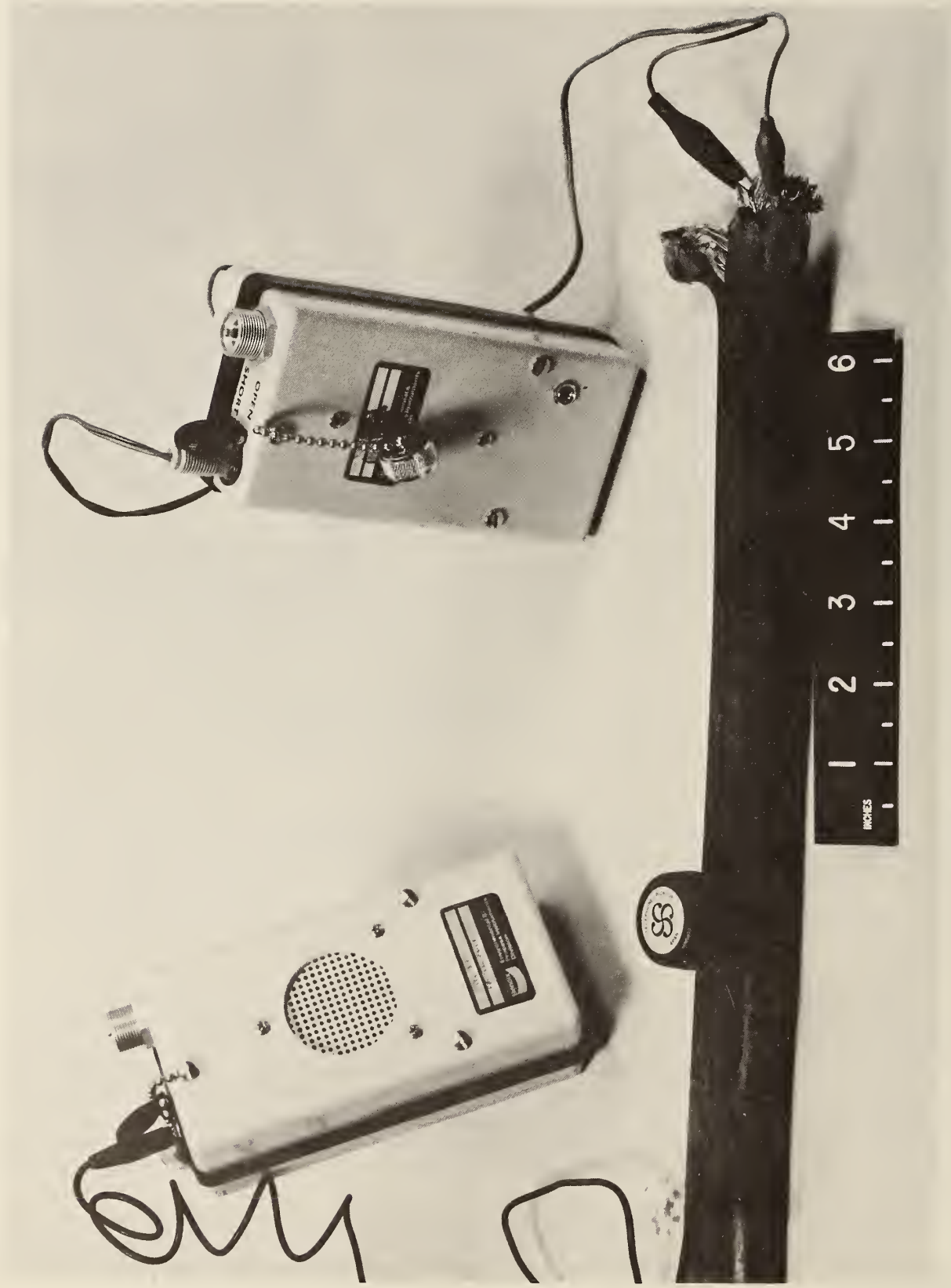


FIGURE 9. - Miniaturized tone set.

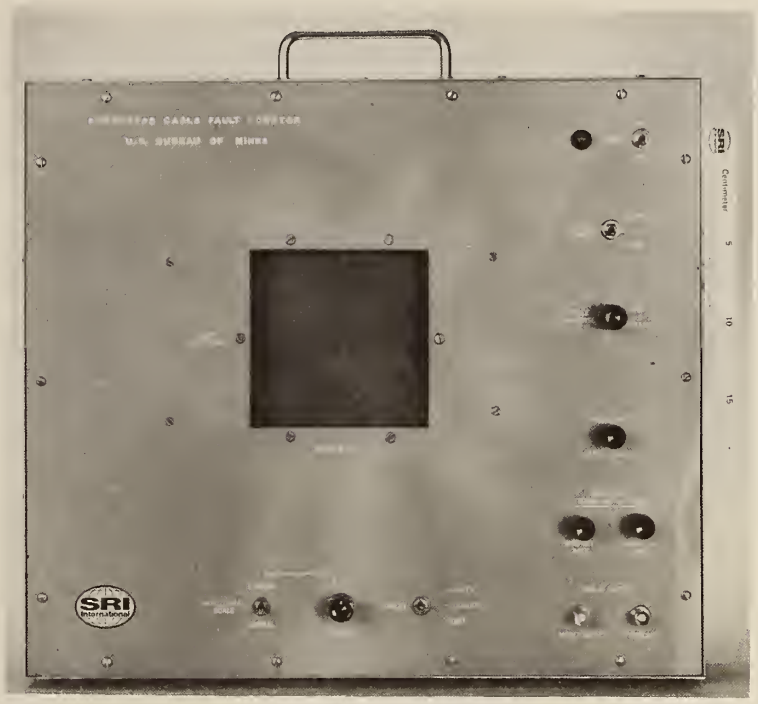


FIGURE 10. - Swept-frequency cable sounder.

The round-trip time is then related to the distance along the cable by digital circuitry. Rather large amounts of energy can be directed into the cable in this way without necessitating a high applied voltage, since each frequency carries its own "bundle" of energy. Because of this and the rather high frequency range utilized, the signal can penetrate shielding; and the precise location of a fault can be bracketed by placing a hand (which can now be considered as embodying the probe function) on the cable at various positions along the length while noting the changes in the display at the terminal end. The relationship between the signal anomalies caused by the presence of the hand and those resulting from the faults provide the requisite location information. The high energy level and high frequency can be utilized in another way in that the signal can be induced into the cable instead of being supplied by a direct metallic connection. This means that the entire input and output system can be acting over a distance of several feet instead of over the entire length of the cable, thus the effect of percentage inaccuracies would be minimized. Both the terminal-connected apparatus and the induction device are soon to be supplied to the Bureau in the form of field-test models for trial in various applications and improvement as necessary.

Of the various cable-fault-locating methods described, the type that is most universal while being commercially available for underground use is the TDR. This is a fairly expensive and delicate system. The infrared devices are also readily available in "pistol" or "rifle" form, but this is not the ideal shape for traversing a cable, owing to the difficulty of guiding it so as not to have the indication vary widely because of changes in the relationship between cable diameter and field of view. Infrared is, also, essentially restricted to the location of shunt faults. The tone generator and cable-route tracer combination, which has been successfully used for locating shunt faults, may have some application to finding series faults, and is also commercially available; however, it is not functional for shielded cables. Recent experimental work may change this situation.

If we can eventually establish that a given fault-locating system is highly effective in a large majority of practical cases encountered in

underground mining, perhaps it will become desirable in the future to incorporate a cable-fault-locating device in every load center, to be connected to the faulted cable or traversed along its length as soon as the fault occurs, and before it has time to change character.

CONCLUSION

Several methods of locating cable faults have been discussed. Apparatus capable of implementing these methods is, in some cases, available commercially; however, in other cases, only Bureau of Mines prototypes or test models are available. It is possible to evaluate Bureau units at the particular mine site; and it may be possible to interest a manufacturing organization in fabricating them. Although the Bureau is limited in its ability to arrange the latter function; it will do what can be done to simplify the transition from test model to commercial product.

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